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Development of a Ground Resistivity Technique for Locating Buried Granular Deposits

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Development of a Ground Resistivity Technique for Locating Buried Granular Deposits

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Abstract:	The objective of the study was to evaluate and develop inductive ground resistivity techniques for identifying and mapping buried granular deposits. In some parts of Ontario, surficial sand and gravel deposits are being depleted. In these areas, there are sand and gravel deposits that are partially or wholly buried under glacial lake sediments and/or glacial till. The report describes the investigation of a glaciofluvial gravel deposit in one of these areas. The investigation consists of a combination of a study of Quaternary geology of the area and ground resistivity techniques. Ground resistivity surveys were carried out for shallow penetration (6 m) and for deeper penetration (15 m) using two different instruments. The two survey results were analysed and the most likely locations for sand and gravel were predicted. Thirty-one auger holes were drilled and it was concluded that good correlation existed between the ground resistivity results and the augered borings. A gravel deposit was located below 8 m of silt and till but it was not of sufficient extent for exploitation. As part of the project, a *Manual for Use of Ground Resistivity to Locate Burial Granular Deposits* was prepared by the authors, which was published separately.
Comments:	Project was successful, but the system requires further practical application to prove its useability.
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SUMMARY

This study was undertaken to evaluate and develop inductive ground resistivity techniques for identifying and mapping buried granular deposits. In addition, a user manual detailing the resistivity methods used for identifying and mapping buried granular deposits has been prepared for use by MTC technical personnel. Finally, the study allowed a detailed evaluation of a test site in southern Ontario that was expected to contain a buried granular deposit.

The test site selected is approximately 1.2 km by 1.3 km and is located in Howard Township, Kent County, northeast of Chatham, Ontario.

A survey grid, the configuration of which was decided upon by the study team, was established at the test site. A topographic survey was undertaken using stadia methods and the data obtained were used to produce a topographic map of the site.

Inductive resistivity surveys were performed with Geonics Limited instruments which sensed down to a depth of 6 m (the EM 31) and 15 m (the EM 34-3). Apparent conductivity readings were recorded at regular intervals along the grid lines and were later plotted and interpolated to produce conductivity contours and profiles. The resistivity survey data were analysed in an attempt to predict the soil stratigraphy associated with the various readings that were obtained.

Based upon the results of the resistivity surveys, 31 test hole locations were selected by the study team members. The test holes were drilled and logged by MTC personnel with assistance from Bird & Hale Limited staff.

Additional information obtained from documents and personal consultation was analysed to determine the Quaternary and bedrock geology of the area.

Conventional granular investigation methods undertaken at the test site prior to and during the study were unsuccessful in delineating the extent of buried granular deposits.

The results of the test drilling program substantiated the predictions made regarding the soil types expected from the resistivity survey results. Therefore, the inductive resistivity surveys were successful in delineating areas of granular material potential.

Detailed soil and conductivity profiles along test lines indicate that the conductivity data fairly well represent the variations in the types of unconsolidated earth materials within the exploration depths of the instruments used. The granular material found at the surface has limited suitability, being primarily of a select subgrade type material. The buried material, as determined by the borehole logs, is of a better quality with the potential for use as granular A and B type materials. However, the better quality material is covered by too great a depth of overburden to be extracted economically at this time.

In general, inductive resistivity surveys can be used to delineate areas with granular material potential and to eliminate areas where further work would most likely be pointless. Furthermore, the method can be used to extrapolate the Quaternary geology between drill holes, thus reducing cost of the test drilling.

Test lines should be surveyed with the EM 31 and EM 34-3, or similar electromagnetic terrain conductivity measuring instruments, at a well-known, economical granular deposit. In addition to determining the conductivities associated with this particular deposit, the survey would also provide benchmark data which could be used when evaluating other terrain conductivities which are obtained in the same general geology conditions.

It is also suggested that the three survey lines, F, N and S should be surveyed using a coil separation of 20 m and the vertical co-planar dipole coil configuration, and these lines should all be repeated using 40 m coil separation, with observations being made at both coil configurations. The results of the additional work would complete the suite of electromagnetic conductivities which then can be used to compute thickness and true conductivities to be compared with the geologic data from drilling.

The test surveys clearly indicated the usefulness of the method to locate granular material -- excepting the inherent limitations imposed by the method, such as the effect of silt or water content which increases the conductivity readings of granular material thus making detection more difficult. To encourage use of the method, it would be advantageous to organize seminars for field personnel to acquaint them with the principles of the method, instruments, survey techniques, limitations, and with the preliminary evaluation of the survey data.

The study objectives, as stated in this report, have been achieved in full.

1/ INTRODUCTION

1.1/ Background

Throughout Ontario there are numerous extensive areas in which surface sources of granular material are non existent, severely limited, or have been depleted. In the majority of these areas, aggregate prices are relatively high, aggregates must be imported from considerable distances (in some instances from the USA), and the qualities of aggregates that are available are poor and are severely limited. There are geological indications in some of these areas, such as southwestern Ontario, that buried granular deposits are present. However, the available exploration methods (i.e., test drilling, etc.) have proven very costly and have been unsuccessful in locating these buried deposits. The reason for the low success rate relates to the lack of an organized and reliable exploration technique to locate test holes optimally. In some regions government agencies, especially the MTC, and municipalities and private aggregate producers and users (i.e., pit operators and building contractors) have terminated exploration for granular materials and must cope with inflated aggregate costs. In other areas, where shortages of aggregates are more severe, exploration is being conducted using available methods with poor success rates. Consequently, the development of a more effective method for identifying and mapping buried granular deposits would result in substantial savings for government agencies and private aggregate producers and users. This has been made possible by the recent development of geophysical equipment suitable for shallow depth penetration and evaluation of overburden materials.

The immediate cost savings likely to result from development of an effective method for identifying and mapping buried granular deposits will occur primarily in the following categories.

- The identification of granular deposits in areas where sources are currently limited or non-existent will likely result in reduced local market prices for aggregates. This will result in competitive pricing and reduced transportation costs.

- The cost of exploration for buried granular deposits will be reduced. Also, the poor success rate of these exploration programs will be improved.

- This study has been conducted in an area of southwestern Ontario in which there is a strong demand and severe shortage of aggregates. Identification and evaluation of a granular deposit in this area would result in an immediate and direct cost saving to MTC, local municipalities, and other aggregate users.

Two indirect and longer-term cost savings which may result from the development of an effective method for identifying buried granular deposits are described below.

- In areas where known granular reserves are limited, it is occasionally necessary to apply modified specifications, and design to permit the use of aggregates which do not satisfy standard applications. This often results in increased long-term maintenance costs. However, in some of these areas, buried granular deposits, which have not been identified using available exploration techniques, may contain aggregates of acceptable quality for a wide range of uses.

- The difficulty encountered in identifying buried granular deposits using conventional methods has resulted in numerous areas that are underlain by granular material being developed for uses that prevent future extraction of the aggregate. Development of an effective method for identifying and mapping these buried deposits would permit consideration of these resources during land use planning. This would permit these areas to be designated as aggregate reserves for future use. This is applicable to areas where surface deposits are non-existent or limited as well as for long-term planning in areas where surface sources are currently available.

The MTC recognized the need for an effective method of identifying and mapping buried granular resources. As a result, Bird & Hale Limited was commissioned to investigate the suitability of remote sensing techniques, including geophysical methods, for locating and mapping buried granular deposits. The commissioned study revealed that recently developed resistivity techniques offer the greatest potential for use as a method for identifying and mapping these deposits. Subsequently, Bird and Hale Limited submitted to the Research and Development Branch of the MTC, a proposal for a study to evaluate the suitability of recently developed terrestrial resistivity techniques as a method for identifying and mapping buried granular deposits. Authorization to proceed with this project was received on August 1, 1985.

1.2/ Objectives

The primary objectives of this study are:

1/ To develop a terrestrial resistivity method for identifying and mapping buried granular deposits.

2/ To prepare a user manual, suitable for use by Ministry technical personnel, that details the resistivity method for identifying and mapping buried granular deposits.

3/ To evaluate, in detail, a test site in southwestern Ontario that is expected to contain a buried granular deposit.

1.3/ Scope

The study was limited to evaluation of one test site in southwestern Ontario. The test site is approximately 1.2 x 1.3 km.

Two separate resistivity surveys were conducted on the test site. The resistivity equipment consisted of the EM 31, which has a maximum sensing depth of 6 m, and the EM 34-3 which senses down to a depth of 15 m when operated with a coil separation of 20 m in the horizontal dipole mode.

The resistivity survey grid line spacing was determined to be 60 m. Readings were taken every 10 m along the grid lines with the EM 31 and every 20 m with the EM 34-3. The grid line spacing and frequency of resistivity readings along the grid lines were determined by the geophysicists on the study team.

With the exception of a limited number of borings conducted by the Ontario Ministry of Natural Resources, test drilling and logging was conducted by MTC staff from the Southwestern Region office. Staff from Bird and Hale Limited were on-site to observe the drilling operations. Drilling was conducted with a MTC Flight auger drill which had a maximum depth capability of 12.5 m.

The soil composition and moisture content data obtained during the test drilling program were suitable for interpretation of resistivity data obtained using the EM 31. However, interpretation of EM 34-3 resistivity data would be enhanced by acquisition of information on both subsurface soil composition and moisture content to a depth of 15 m.

The responses obtained and the suitabilities of the resistivity methods for identifying and mapping buried granular deposits are specific to the terrain (i.e., geology, soil moisture content) conditions that prevail on this site and do not represent the responses or suitabilities that may occur under different terrain conditions.

1.4/ Study Team

The study team consisted of:

- Mr. S.J. Glenn Bird, project director, and
  Mr. Wm. Moore, project manager, glacial geologist,
  (both of Bird & Hale Ltd.);
- Mr. Frank Jagodits, geophysicist, Excalibur International Consultants Limited; and
- Mr. Duncan McNeill, geophysicist, Geonics Limited.

Messrs. Moore and Bird were responsible for co-ordinating the study and therefore kept in close contact with Messrs. Gruspier and Katona of MTC. Mr. Moore interpreted the glacial geology of the site through airphoto interpretation, analysis of the test drilling data, and review of existing documents. Mr. Jagodits was responsible for analysing and correlating the resistivity and soils data obtained during the study. Mr. McNeill interpreted the resistivity data and, along with Mr. Jagodits, determined the optimum resistivity equipment and survey techniques to be used in the study.

The entire study team had input into the resistivity survey grid alignment and the locations of test drilling sites.

Personnel from Bird & Hale Limited conducted all the field components of the study except the test drilling; this was performed by MTC personnel from the London Region Office, with assistance from Bird & Hale staff.

1.5/ Study Method

A potential test site and an alternate test site were identified in Howard and Camden Townships, Kent County, southwestern Ontario.

Airphoto interpretation and review of available data permitted mapping of all relevant terrain conditions and preliminary determination of the Quaternary geology of the test site. References used are listed in Appendix A. Based on this information, the optimum geophysical survey grid alignment was determined. A total of 23 survey grid lines were established on the site using compass and chaining methods.

A topographic survey of the study site was conducted using stadia methods, and a contour map having contour intervals of 1 m was prepared. Terrestrial resistivity surveys of the site were conducted using the EM 31 and EM 34-3. The results of these surveys were plotted to produce conductivity (reciprocal of resistivity) profiles along selected grid lines and contour maps of the entire site for the data obtained with each of the instruments.

The conductivity profiles and contour maps were analysed to facilitate identification of the optimum locations for test drilling sites. The results of test borings conducted on the site by the Ministry of Natural Resources were also used during selection of the test drilling sites. A total of 34 drilling sites were selected in areas which were expected to be representative of the various terrain conditions that occur within the site. Test drilling was conducted by MTC personnel. Samples of representative soil strata were obtained for subsequent laboratory analysis by MTC.

Topographic and soil profiles were prepared for the same selected grid lines for which the conductivity profiles were prepared. Isopach maps of the surficial, buried and total granular material were prepared. The soils data were analysed to facilitate interpretation of the Quaternary geology of the site.

The resistivity, topographic, soil composition and moisture content data were evaluated to determine the applicability of the resistivity methods used to identify and map surface and buried granular material for the terrain conditions that prevail on the test site.

1.6/ Summary of Conclusions and Recommendations

1. Conventional granular investigation methods were performed at the test site. Airphoto interpretation was unsuccessful in locating buried granular deposits. Random test hole drilling yielded a relatively high success rate in locating buried granular deposits; however, experience has shown that this type of investigation is usually unsuccessful and the results obtained at this test site are the exception to the rule. In addition, the results of the random test hole survey cannot be relied upon to delineate the extent of the buried granular deposits without further, more detailed test hole surveys.

2. Based upon the results of the electromagnetic terrain conductivity surveys, two regions of differing electrical properties were delineated within the test site.

   These include:

   a) The southern half of the test site where relatively high apparent conductivity readings were recorded with both instruments indicating conductive clays, tills and sandy silts. Restricted areas of lower apparent conductivity were recorded by the EM 31, indicating isolated pockets of surface sands. However, as a whole, this area can be considered as lacking in granular material potential.

b) In the northern half of the study site, lower EM 31 apparent conductivity readings were noted, indicating sands or silty sands at surface. In addition, this area exhibited lower EM 34-3 apparent conductivity readings, indicating deeper and/or thicker granular material deposits.

3. The results of the test drilling program substantiated the predictions made regarding the soil types expected from the resistivity survey results. Therefore, the inductive resistivity surveys were successful in delineating areas of granular material potential.

4. Detailed soil and conductivity profiles along three test lines indicate that the conductivity data fairly well represent the variations in the types of unconsolidated earth materials within the exploration depths of the instruments used.

5. The test drilling and resistivity survey data have contributed to the understanding of the Quaternary geology of the area, which was assumed to be fairly complex.

6. The granular material found at the surface has limited suitability due to a high percentage of fines, and is suitable only for select subgrade material. The buried granular material, as determined by borehole sampling, is of better quality with possible suitability for granular A and B aggregates. However, this granular material is covered by too great a depth of overburden to be extracted economically at this time.

7. In general, inductive resistivity surveys can be used cost-effectively to delineate areas with granular material potential and to eliminate areas where further work would most likely be pointless. Furthermore, the method can be used to extrapolate the Quaternary geology between drill holes, thus reducing the cost of test drilling.

8. Test lines should be surveyed with the EM 31 and EM 34-4 or similar electromagnetic terrain conductivity measuring instruments at a well known, operating, buried granular deposit such as the Pinehurst deposit. The survey would provide conductivities associated with this particular deposit, including responses for coarse aggregate (gravel) which were not obtained during this study. The survey would also provide benchmark data which could be used when evaluating terrain conductivities which are obtained in the same general geology conditions.

9. It is also suggested that the three survey lines, F, N and S should be surveyed using a coil separation of 20 m and the vertical co-planar dipole coil configuration. These lines should also be repeated using 40 m coil separation, with observations being made at both coil configurations. The results of the additional work would complete the suite of electromagnetic conductivities which then can be used to compute thickness and true conductivities to be compared with the geologic data from drilling. The additional data would also demonstrate the variations of the apparent conductivity with depth.

10. The test surveys clearly indicated the usefulness of the method to locate granular material. The inherent limitations imposed by the method, such as the effect of silt or water content which increases the conductivity readings of granular material, does, however, make detection more difficult. In order to promote the use of the method, it would be most advantageous to organize seminars for field personnel to acquaint them with the principles of the method, instruments, survey techniques, and limitations, and with the preliminary evaluation of the survey data.

2/ DEMONSTRATION PROJECT

This section of the report describes the procedures used to accomplish the objectives of this study and the results of analysis of the data obtained.

The procedures are presented in the order in which they were conducted. Analysis of additional data, such as the borehole data compiled by the Ministry of Natural Resources was not conducted during the initial stages of the study to ensure that interpretation of the resistivity survey results and subsequent identification of the optimum test drilling sites would not be influenced by detailed knowledge of the subsurface soil and groundwater table conditions of the site.

2.1/ Test Site Selection

The test site was selected through consultation between Mr. Z.L. Katona, Senior Soils and Aggregate Engineer, Soils and Aggregate Section, MTC, and Mr. S.J. Glenn Bird of Bird & Hale Limited. Mr. Katona obtained suggestions regarding potential test sites from MTC Regional offices. The suggested sites were then reviewed to identify a test site and an alternative test site that best satisfied the site selection criteria. The following is a summary of the test site selection criteria:

- The site was selected in a portion of the province in which known sources of granular material are limited.
- Demand for granular material is high.
- There is a strong indication that buried granular deposits occur.
- A test site with approximate dimensions of 1.5 by 1.5 km is available.

An alternative test site was identified in the event that access to the potential test site was not granted by the private land owners or if, during the initial stages of the study, it was determined that the test site did not satisfy the primary site selection criteria.

The test site is situated in Howard Township in Kent County northeast of Chatham, Ontario (see key maps, Figures 2.1 and 2.2).

The Chatham area was selected for a test site because surface deposits of sand and gravel are meagre and generally of poor quality; however, the potential of the area for buried sand and gravel is believed to be high (Wilson, 1981). The results of limited test drilling conducted on the test site by the Ontario Geological Survey, Ministry of Natural Resources, indicates the occurrence of buried granular material. Also, the anticipated demand is moderately high in this area for aggregate to be used in reconstruction and resurfacing projects undertaken by MTC and municipalities.

2.2/ Design of the Field Program

Prior to designing the field program Messrs. Gruspier, Katona and Barber of MTC and Messrs. Bird and Moore of Bird & Hale Limited visited the test site to discuss the project with the landowners and obtained their approval to proceed.

Airphoto interpretation, site inspection and preliminary review of selected available data permitted evaluation of terrain conditions and preliminary determination of the Quaternary geology of the site. A series of well-drained topographic highs were observed to form a discontinuous ridge which traverses the central portion of the site in an east-to-west direction. It was anticipated that this ridge may be the topographic and soil drainage surface expression of a formation bearing buried granular material. To ensure that the survey grid lines traversed and provided cross-sections throughout this feature it was decided that the grid lines should be oriented northwest-to-southeast, parallel to Kent County Road 15. The configuration of the geophysical grid shown on Drawing No. 1.

Figure 2.1/ Key Map of Test Site

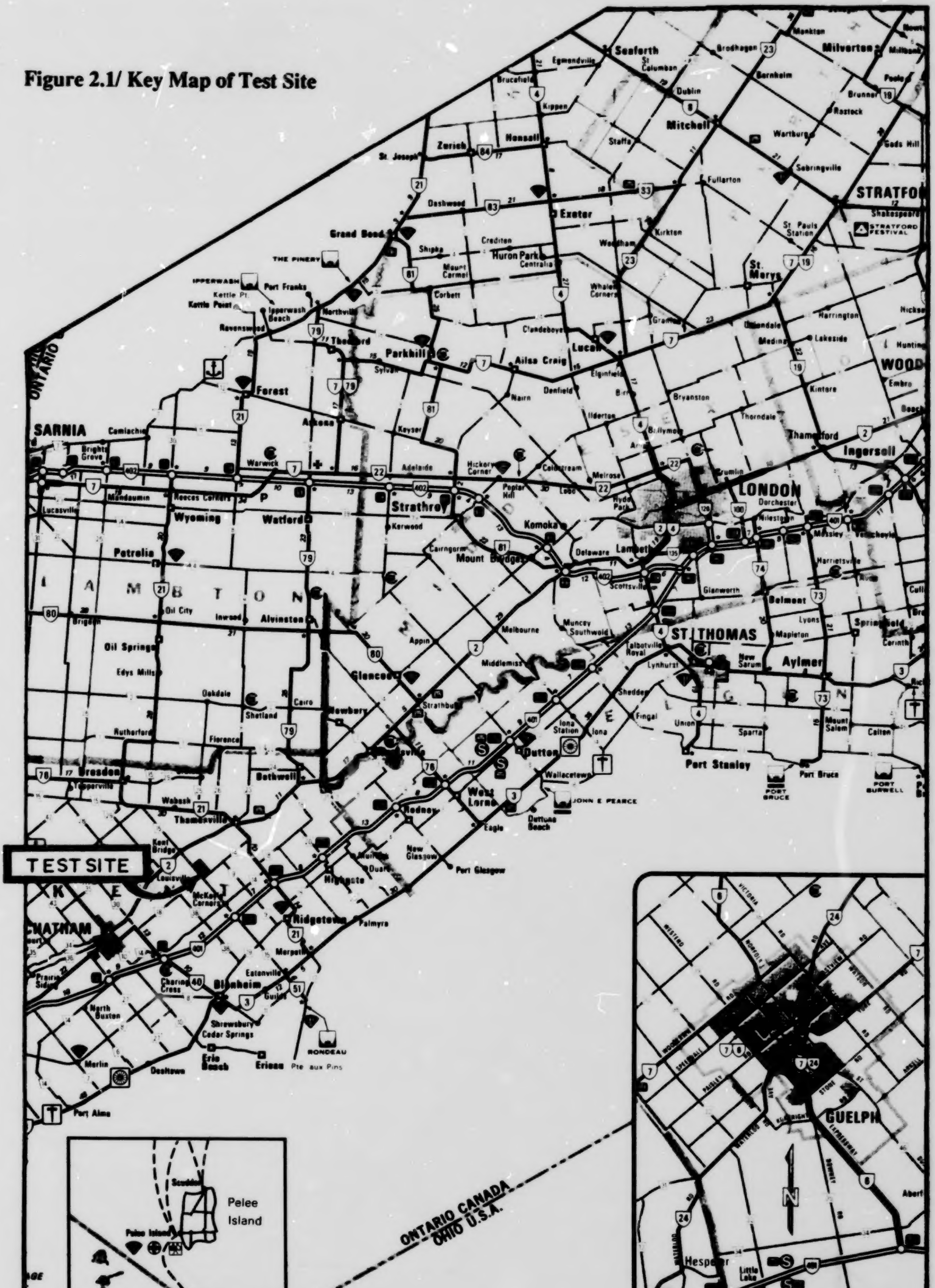
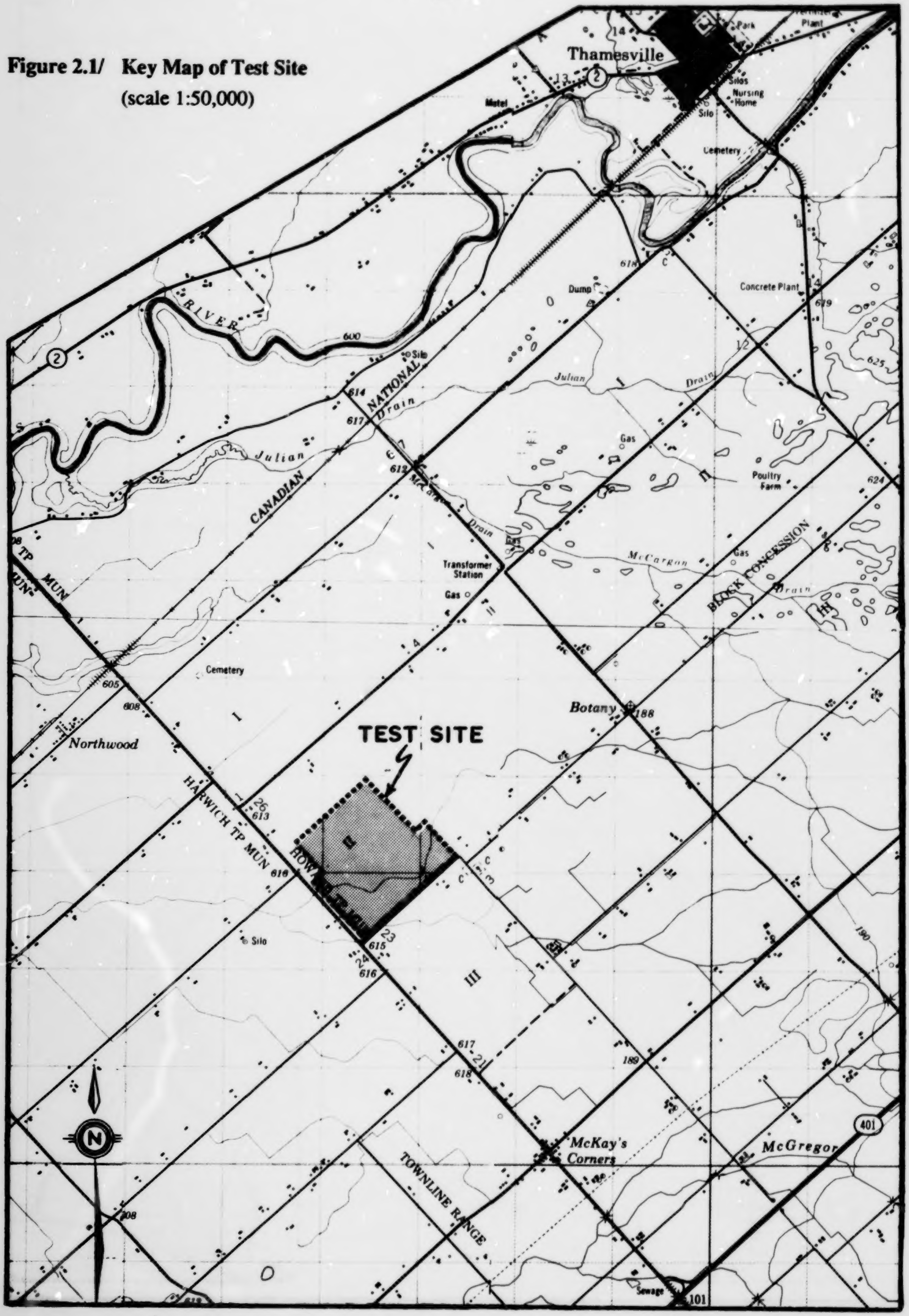
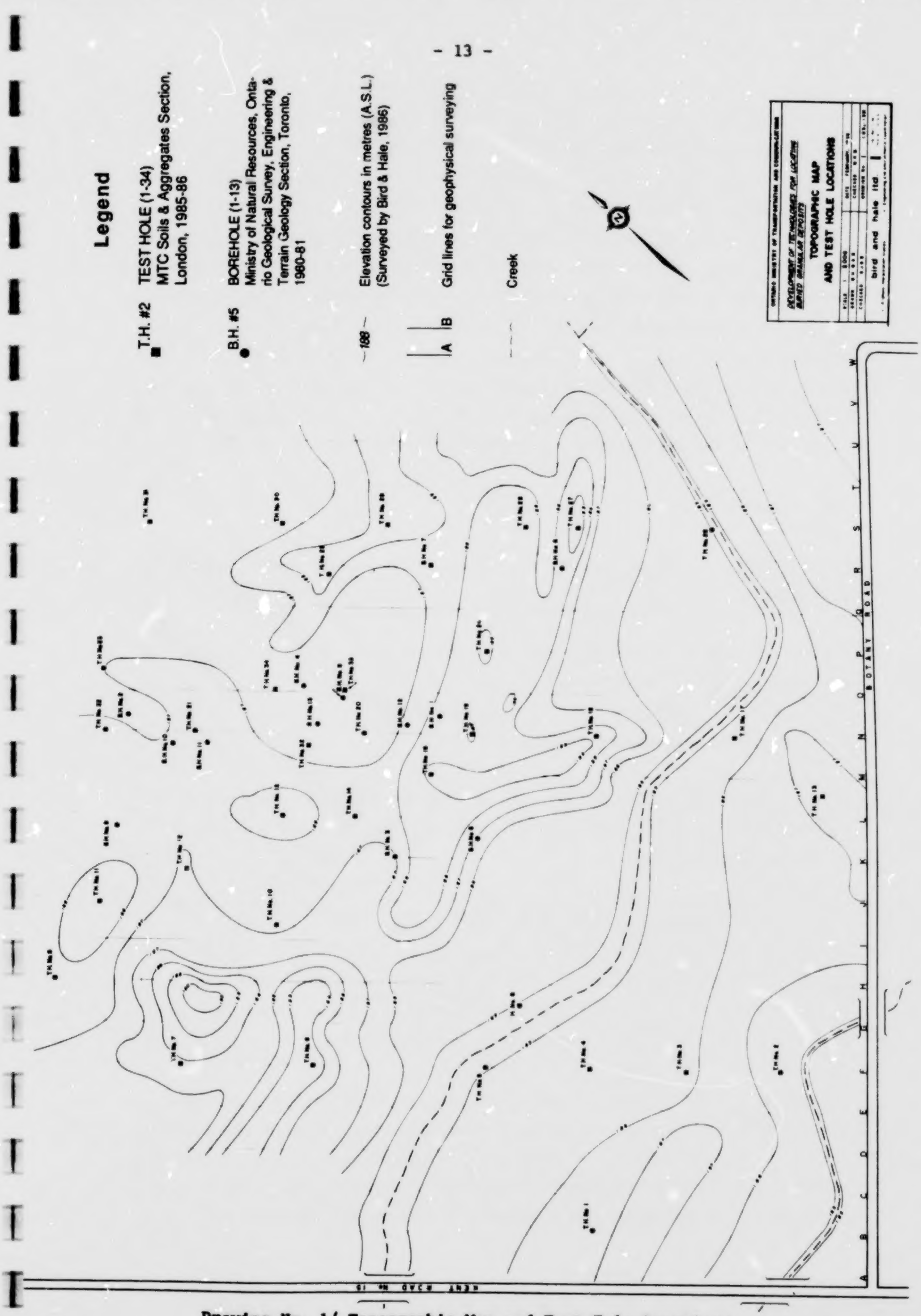

TEST SITE
SARNIA
LONDON
ST. THOMAS
CHATHAM
STRATFORD
GUELPH
Pelee Island
ONTARIO CANADA
OHIO U.S.A.

Figure 2.1/ Key Map of Test Site
(scale 1:50,000)


Thamesville
Park
Silos
Nursing Home
Silo
Cemetery
Motel
RIVER
Dump
Concrete Plant
Julian Drain
NATIONAL
CANADIAN
McCargon Drain
Gas
Poultry Farm
Transformer Station
BLOCK CONCESSION
Cemetery
Botany
188
Northwood
TEST SITE
HARWICH TP MUN
HOWARD TP MUN
TOWNLINE RANGE
McKay's Corners
McGregor
401
Sewage
101
Silo
189
190
TP MUN


Legend
T.H. #2 TEST HOLE (1-34)
MTC Soils & Aggregates Section, London, 1985-86
B.H. #5 BOREHOLE (1-13)
Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81
188 Elevation contours in metres (A.S.L.)
(Surveyed by Bird & Hale, 1986)
A B Grid lines for geophysical surveying
Creek
N
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS
TOPOGRAPHIC MAP AND TEST HOLE LOCATIONS
SCALE 1 : 2000
Bird and hale ltd.
BOTANY ROAD
KENT ROAD No 15
A B C D E F G H I J K L M N O P Q R S T U V W

Drawing No. 1/ Topographic Map and Test Hole Locations

2.3/ Establishment of Test Grid

The test grid was established by a two-man crew in September, 1985, using compass and chaining methods. Starting at the southwest corner of the test site, base line stations were staked every 60 m along the southern boundary of the test site (the north right-of-way of Botany Road). The azimuth of Kent Country Road No. 15 (along the west boundary of the study site) was determined to be 320 degrees. Working north from the base line stations, the grid lines were flagged using this azimuth. Reference stations for resistivity readings were flagged every 20 m along the grid lines during the resistivity surveying (see Section 2.5.2 for details).

2.4/ Topographic Survey

A topographic survey of the study site was undertaken utilizing stadia principles.

The survey data were interpolated to produce a topographic contour map of the study site (see Drawing No. 1).

2.5/ Inductive Resistivity Surveys

Resistivity surveys of the test site were carried out by a two-man crew in October, 1985. The two resistivity surveys are described in the following subsections.

2.5.1/ EM 31 Survey

The EM 31 survey was performed after the EM-34-3 survey as this enabled the survey crew to reference the readings to the 20 m stations that were flagged during the EM 34-3 survey (see Section 2.5.2).

Initially, the EM 31 was used with the corresponding analogue recorder which plotted continuous resistivity readings along the grid lines. This proved to be very awkward as the rows of corn, present during the survey, severely inhibited the movement of the two crew members who were linked together by the connection cord between the EM 31 and the recorder.

It was decided, after consultation with Geonics Limited personnel, to discontinue the use of the recorder, as sufficient data could be obtained by recording resistivity data manually every 10 m along the grid lines.

The EM 31 operating in vertical dipole mode with the analog recorder connected is shown on photograph No. 1. Note that the instrument panel is horizontal in the vertical dipole mode. The EM 31 is shown collapsed on photograph No. 2. Both photographs can be found in Appendix B.

The test lines were walked at a moderate pace and conductivity readings were recorded. Odd numbered stations (10, 30, 50 m, etc.) were paced from even stations (20, 40, 60 m, etc.) flagged during the EM 34-3 survey.

To ensure that the most accurate readings were recorded, the survey crew paused for one or two seconds to allow the instrument to adjust to the correct reading. In addition, the conductivity range switch was always set such that the conductivity meter read in the upper two-thirds of the scale. A range of 30 mmho/m (millimhos/metre) was usually sufficient; however, the range occasionally had to be increased to 100 mmho/m when conductivity readings exceeded 30 mmho/m.

2.5.2/ EM-34-3 Survey

Before field surveying commenced, the coil separation meter on the receiver panel was checked for accuracy. Photograph No. 3, Appendix B, shows the receiver. The coils were spaced at approximately 20 m and were held in the horizontal dipole mode; upright, on their sides, perpendicular to the ground surface. Care was also taken to insure that the coils were held in the same plane, the axis of the coils being parallel to each other. Photograph No. 4 shows the correct method of holding the coils. The separation selector switch was set at 20 m and the distance between the coils was adjusted until the correct reading was obtained on the coil separation meter. The distance between the coils was measured and found to be correct.

During surveying, the conductivity range switch was set such that the conductivity meter read in the upper two-thirds of the scale. A range of 30 mmho/m was used for the entire test site.

Starting at a base line station, the transmitter operator moved the transmitter coil up-line until the correct coil separation was noted on the receiver panel. The receiver operator then recorded the conductivity reading while the transmitter operator flagged the 20 m station. Subsequently, the receiver operator moved up-line to the station previously flagged while the transmitter operator moved up-line to a new station. The procedure was then repeated at this station and at all subsequent stations.

2.6/ Analysis of the Inductive Resistivity Survey Data

2.6.1/ General Comments

In order to appreciate the results obtained by the two instruments, it is worthwhile to review a few theoretical considerations. For detailed discussion of the theory of electromagnetic conductivity measurements, refer to Appendix C.

The conductivity obtained with the EM 31 and the EM 34-3 instruments will be the true conductivity of the ground if the conductivity is uniform within the depth of exploration (homogeneous half-space). If there are layers of different conductivity within the depth of exploration (horizontally stratified earth) then the observed conductivity will be an apparent conductivity. It is always assumed that the observations represent apparent conductivities unless it is known from comparison of geologic and geoelectric data that there is only one geoelectric layer within the depth of exploration at the coil separation and configuration used.

Both instruments can be used in two modes of coil configuration:

- vertical co-planar dipoles (coils horizontal and co-planar); and,
- horizontal co-planar dipoles (coils vertical and co-planar).

Figure 6 of Appendix C shows that near-surface material makes a small contribution to the apparent conductivity when the vertical co-planar coil configuration is used. On the other hand, relative contribution increases from near-surface material when the horizontal co-planar dipole configuration is used. The EM 34-3 test survey employed the horizontal co-planar dipole coil configuration. Thus, it should be kept in mind that the relative contribution from the near-surface materials to the overall apparent conductivity will be larger than the contributions from layers at depth.

The apparent conductivity obtained by the EM 31 and the EM 34-3 is dependent upon the true conductivity of the layers, the thickness and the depth of the layers, and the coil separation. Drilling of the test area confirmed that the ground is stratified. Consequently, the observed conductivities are apparent rather than true. Therefore, it would be instructional to examine the effect of varying the coil separation, which affects the depth of penetration of the instrument. The apparent conductivities obtained from the various depths of penetration will further aid in analysing the true conductivities of the layers. This exercise will also contribute to understanding of the apparent conductivity maps of the test site (discussed later in this report).

The generalized stratigraphic sections of the test site are given in Figure 3.3, with descriptions of stratigraphic units in Table 3.1. Regarding the electromagnetic resistivity measurements, the aeolian sand deposits and the shallow water lacustrine sand deposits can be combined into one single electric layer, which could have a true conductivity of about 5 mmho/m. The electrical properties of the underlying deep water lacustrine clay and silt and flowtill are more than likely very similar and, once again, can be treated as a single electric unit with a true conductivity of approximately 15 mmho/m. The ice contact/outwash units, sand and gravel, are below the till and underlain by Huron/Ontario-Erie till, which can have the same true conductivity as the till above (15 mmho/m). The thickness and depth of the combined intertill gravel and sand layers can vary considerably. The true conductivity of this gravel and sand would be about 3 mmho/m. It is unlikely that the bedrock shale was penetrated (sensed) by the geophysical instruments.

The relative contribution from each of the layers can be determined using Figure 11 of Appendix C and the following equation:

$$\sigma_a = \sigma_1[1-R(Z_1] + \sigma_2[R(Z_1) - R(Z_2)] + \sigma_3[R(Z_2) - R(Z_3)] + \sigma_4 R(Z_3)]$$

where: σ_a = the apparent conductivity

σ_1, σ_2, σ_3, and σ_4 = true conductivity of the layers

Z_1, Z_2 and Z_3 = depth to the top of the second, third, and fourth layers

$R(Z_1)$, $R(Z_2)$, $R(Z_3)$ = values obtained from Figure 11, Appendix C

The values for R(Z) are taken from the vertical axis of Figure 11, Appendix C, for the appropriate value of Z/s on the horizontal axis. As s, the spacing between the coils in metres, is 20 m in this case, then for a 3 m thickness of first layer in this example, $Z/s = 3/20 = 0.15$. The corresponding value for $R(Z_1)$ is therefore 0.85, as shown in Figure 11. The total depth of 13 m is used for $R(Z_2)$, thus yielding a value of 0.35.

The following parameters are used:

• 1st layer:	shallow water lacustrine sand:	σ_1 = 5 mmho/m
	thickness:	3 m
• 2nd layer:	clay and till:	σ_2 = 15 mmho/m
	thickness:	10 m
• 3rd layer:	sand and gravel:	σ_3 = 3 mmho/m
	thickness:	4 m
• 4th layer:	till:	σ_4 = 15 mmho/m
• Coil separation:	20 m	
• Coil configuration:	Horizontal co-planar dipoles	

All of the material below ground surface produces 100% of the instrumental response, the apparent conductivity. The material below 3 m contributes 85% of the total response, leaving a contribution of 15% for the first 3 m.

The material below 13 m produces 35% of the instrument responses, hence the contribution of the 2nd layer is 50%.

The contribution from materials below 17 m is 28%, leaving 7% for contribution from the 3rd layer.

The contributions expressed numerically for the above are:

1st layer: $\sigma_1[1 - R(Z_1)] = 5[1 - 0.85] = 0.75$ mmho/m
2nd layer: $\sigma_2[R(Z_1) - R(Z_2)] = 15[0.85 - 0.35] = 7.5$ mmho/m
3rd layer: $\sigma_3[R(Z_2) - R(Z_3)] = 3[0.35 - 0.28] = 0.21$ mmho/m
4th layer: $\sigma_4[R(Z_3)] = 15(0.28) = 4.2$ mmho/m

----

hence: $\sigma_a = 12.66$ mmho/m

It is quite clear from the above that the major influence is exercised by the 2nd layer, because of its thickness and high conductivity, and by the 4th layer, because of its high conductivity. If the thickness of the first layer increases and/or its conductivity decreases, the apparent conductivity observed by the instrument will be lower. It can also be observed that in order to increase the contribution from the 3rd layer (the sand and gravel) it should be shallower, thicker, and should have lower conductivity and/or the conductivity of the overlaying till would have to be lower.

Another situation may exist when the intertill gravel deposit pinches out. In this situation, the geoelectric section reduces to a two-layer case. Keeping the thickness and the conductivity of the 1st layer the same (3 m and 5 mmho/m), the apparent conductivity will be 13.5 mmho/m, which is only marginally higher than the apparent conductivity computed for the multi-layer situation above. If the thickness of the first layer is increased to 8 m, the apparent conductivity reduces to 9.9 mmho/m.

If there is no covering sand and no intertill gravel, then the geoelectric section reduces to a homogeneous half-space and the observed value will be 15 mmho/m, which is the true conductivity of the till.

The above short exercise also illustrates that minor deviations from the average conductivity of the area can be significant. In granular material exploration, zones of low conductivity are sought assuming that the conductivity of dry sand and gravel is lower than that of the host medium. For the sake of argument it is assumed that the background conductivity represents the true conductivity of the ground (homogeneous half-space). Consequently, zones of lower conductivity could indicate a multi-layer situation in which some of the layers should have lower conductivity than the host, indicating the possible presence of granular material. The assumption that the background conductivity represents the true conductivity is fairly safe for practical purposes. If less conductive units are present in the section, their thicknesses may be too small or they are too deep to substantially influence the apparent conductivity. Consequently, these are unlikely to be of economic interest.

Ideally, one should not find many zones where the apparent conductivity is substantially larger than the background apparent conductivity because it would indicate an unreasonable choice of background. These zones of higher conductivity could indicate that the conductivity of the earth materials increased (the simplest cause), or the introduction of a layer of higher conductivity at the ground surface.

The equation provided above, together with Figure 11 of Appendix C, could be used to predict the electromagnetic conductivities of assumed geologic sections prior to commencing the field work. This should give some idea of the measure influence due to varying thicknesses and conductivities.

2.6.2/ EM 31 Survey

Drawing No. 2 displays the apparent conductivity contours interpolated from the EM 31 readings taken along the grid lines. Also shown are the surficial granular material isopach contours. Section 2.9.1 outlines what the isopach contours represent and how they were developed. The apparent conductivities vary from as low as 8 mmho/m to about 40 mmho/m. The exploration depth of the EM 31 is approximately 6 m.

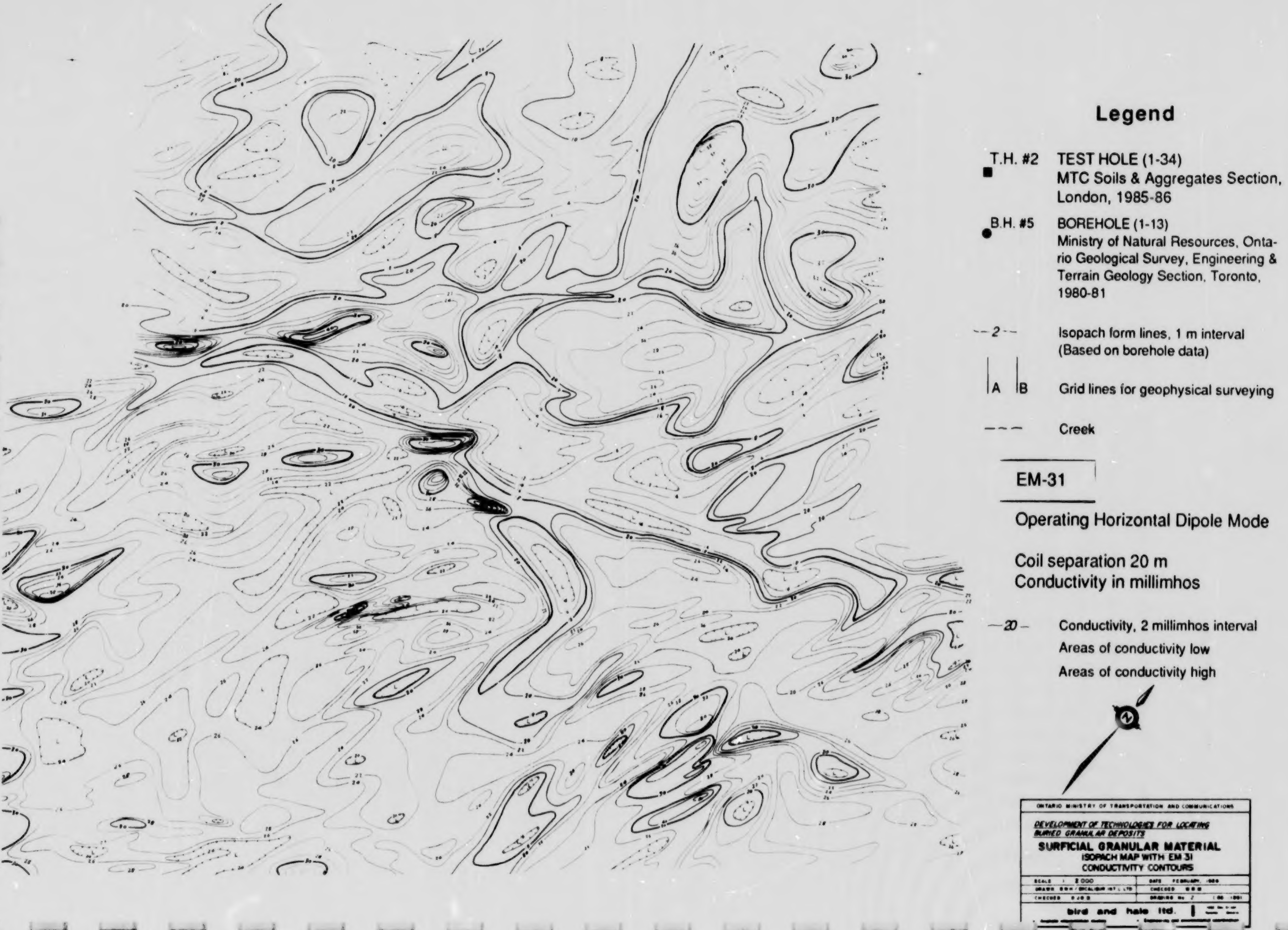
Two distinct regions of background conductivity can be recognized:

- The first region is in the south of the test site -- specifically, it is south of an east-west striking, narrow, conductivity low.
- The second region is to the north of the above.

The southern region is characterized by background apparent conductivities in the order of 25-30 mmho/m, indicating that the conductivity of the clays and tills is fairly high in this area and/or the low conductivity of thin surface sand layers has little effect on the background readings.

There are lower conductivity zones within the southern region where the apparent conductivities decrease to as low as 14 mmho/m -- suggesting that there should be more resistive (i.e., less conductive) material at the surface, or at some depth. In order to see the significance of the lower apparent conductivity, the following example may be computed:

> If the less conductive material is at the surface, a 3 m thick sand layer (conductivity 5 mmho/m) which covers the till (conductivity 30 mmho/m), then the computed apparent conductivity is about 18 mmho/m. To further reduce the apparent conductivity, one should increase the conductivity and/or the thickness of the first layer or reduce the conductivity of the underlying till.


Legend
T.H. #2 ■ TEST HOLE (1-34)
MTC Soils & Aggregates Section, London, 1985-86
B.H. #5 ● BOREHOLE (1-13)
Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81
--2-- Isopach form lines, 1 m interval (Based on borehole data)
A B Grid lines for geophysical surveying
--- Creek
EM-31
Operating Horizontal Dipole Mode
Coil separation 20 m
Conductivity in millimhos
—20— Conductivity, 2 millimhos interval
Areas of conductivity low
Areas of conductivity high
N
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS
SURFICIAL GRANULAR MATERIAL
ISOPACH MAP WITH EM 31
CONDUCTIVITY CONTOURS
SCALE 1 : 2 000
DATE FEBRUARY, 1986
DRAWN
CHECKED
CHECKED
DRAWING No. 2
bird and hale ltd.

Drawing No. 2/ Surficial Granular Material Isopach Map with EM 31 Conductivity Contours

> If the less conductive material (sand and gravel) is placed at depth but still within the depth of exploration, the thickness of the sand and gravel layer would have to be increased and/or the conductivity of the sand and gravel and the conductivity of the till would need to be decreased in order to approximate the observed 14 mmho/m apparent conductivity.
>
> It is concluded that the areas of interest are likely within the zones delineated by the 16-18 mmho/m contours and the chances of the occurrence of significant granular deposits elsewhere in this region are very small. The region would be classified as having extremely low potential.

The situation in the northern region is quite different. The background apparent conductivity has decreased quite substantially, but areas of higher background apparent conductivity are still present. These are found in the northeast and northwest corners and within a zone just north of the east-west striking conductivity low. It is suggested that the increased apparent conductivity indicates the absence of near-surface material (sand) and also the conductivity of the till may have also increased.

The decreased background apparent conductivity of the northern region suggests increased contributions from high resistivity (low conductivity) material, that is sand and/or gravel. The long, narrow, east-west striking low conductivity feature in the south of the northern region describes sand dunes. The prime targets of exploration in the northern region are the zones within the 12 mmho/m contours. However, local closures of the 16 mmho/m contours could also be considered as potentially significant for buried sand and/or gravel exploration.

2.6.3/ EM 34-3 Survey

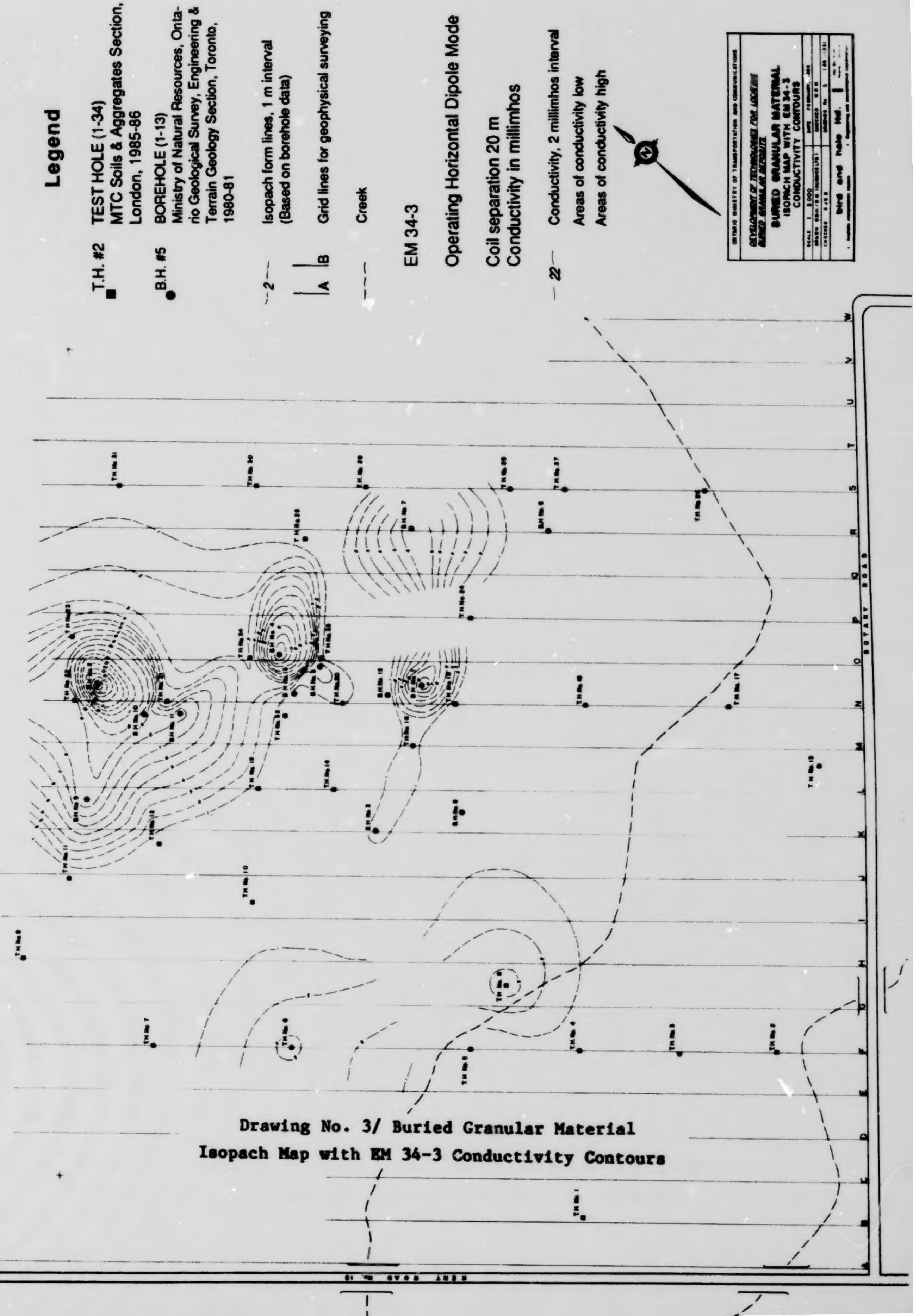
Drawings 3 and 4 display the EM 34-3 conductivity contours with buried granular and total granular isopach contours, respectively (an explanation of the isopach contours is given in Section 2.9.2).

Not unexpectedly, the variations of apparent conductivity are more subdued than on the EM 31 contour map (Dwg. No. 2). The conductivity contours represent contributions for materials down to at least 15 m. The gentle gradients imply that there are no radical changes in the electrical properties of the ground vertically or horizontally. Once again, the test site can be divided into two regions:

- the southern region occupies the area approximately south of the 20 mmho/m contour

- the second region is to the north of the region noted above

The southern region is characterized by apparent conductivities higher than 20 mmho/m, increasing to nearly 30 mmho/m in localized areas. Limited, small areas exist where the apparent conductivity is lower than 20 mmho/m. The high apparent conductivities indicate that the contribution from near-surface granular material or from intertill granular deposits is likely to be very small, especially when the background apparent conductivities of the southern and northern regions are compared. The southern region lacks exploration prospects for granular deposits.


Legend
T.H. #2
TEST HOLE (1-34)
MTC Soils & Aggregates Section, London, 1985-86
B.H. #5
BOREHOLE (1-13)
Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81
2
Isopach form lines, 1 m interval (Based on borehole data)
A
B
Grid lines for geophysical surveying
Creek
EM 34-3
Operating Horizontal Dipole Mode
Coil separation 20 m
Conductivity in millimhos
22
Conductivity, 2 millimhos interval
Areas of conductivity low
Areas of conductivity high
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGY FOR LOCATING BURIED GRANULAR DEPOSITS
BURIED GRANULAR MATERIAL
ISOPACH MAP WITH EM 34-3
CONDUCTIVITY CONTOURS
SCALE 1 : 5000
DRAWN
CHECKED
DATE
CHECKED
DRAWING No. 3
Baird and Parke Ltd.
ROTARY ROAD
B
C
D
E
F
G
H
I
J
K
L
M
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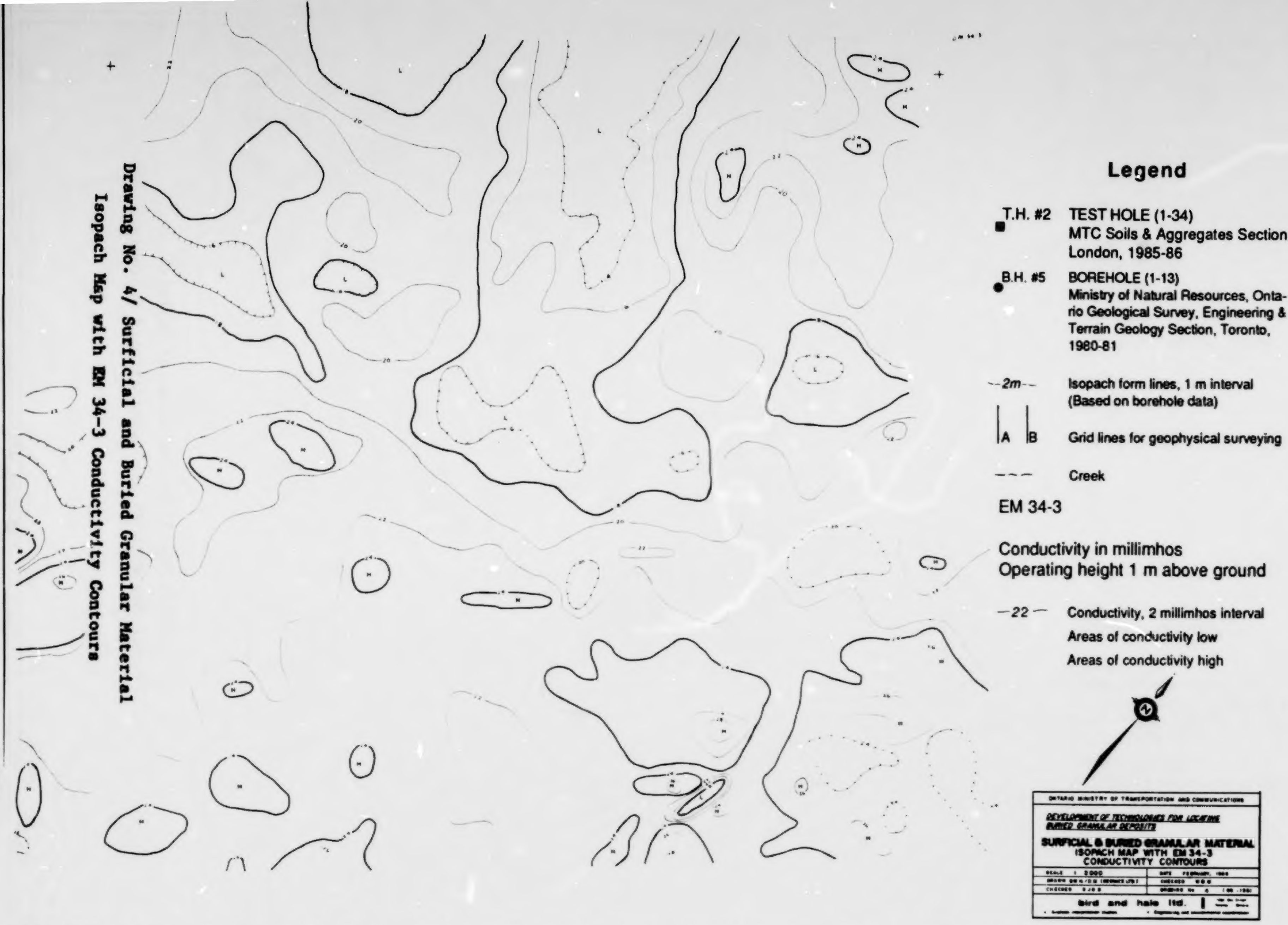
W

Drawing No. 3/ Buried Granular Material

Isopach Map with EM 34-3 Conductivity Contours


Legend
T.H. #2 TEST HOLE (1-34)
MTC Soils & Aggregates Section, London, 1985-86
B.H. #5 BOREHOLE (1-13)
Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81
--2m-- Isopach form lines, 1 m interval (Based on borehole data)
A B Grid lines for geophysical surveying
Creek
EM 34-3
Conductivity in millimhos
Operating height 1 m above ground
—22— Conductivity, 2 millimhos interval
Areas of conductivity low
Areas of conductivity high
N
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS
SURFICIAL & BURIED GRANULAR MATERIAL
ISOPACH MAP WITH EM 34-3
CONDUCTIVITY CONTOURS
SCALE 1:2000
bird and hale ltd.
L
H
20
22
24

Drawing No. 4/ Surficial and Buried Granular Material Isopach Map with EM 34-3 Conductivity Contours

The background apparent conductivities have decreased in the northern region, which may indicate:

(a) more prevalent and probably thicker surficial granular deposits;

(b) somewhat different electrical properties in the geoelectric section; and

(c) thicker or lower conductivity intertill granular materials.

The areas of high conductivity in the northwest and the northeast corners remain, suggesting thicker till clay in these areas.

The apparent conductivity low found along the northern end of lines N and O is the significant feature of the area. A second area of interest is a somewhat broad zone extending from east to west in the central map area. These two areas are the prime targets for testing as they exhibit apparent conductivities measurably lower than the background of about 18-19 mmho/m. The apparent conductivity low at the northern end of Lines H, I, J, and K would have a lower priority because the apparent conductivities are only marginally lower than the background.

2.6.4/ Comparison of EM 31 & EM 34-3 Apparent Conductivity Contour Maps

The depth of exploration of the EM 34-3 instrument is 2.5 times that of the depth of exploration with the EM 31. Hence, the comparison of the two conductivity contour maps of the EM 31 and EM 34-3 data (Dwg. Nos. 2, 3 and 4) should indicate at least qualitatively the variations of materials with depth.

In the southern region, the maps indicate high apparent conductivities, implying thick till overburden. Exceptions to this are the lower conductivity zones on the EM 31 map (Lines L and M). This area of lower apparent conductivity is restricted to the EM 31 map, indicating that the surface, low conductivity material is thin. The inverse situation is also found. In this case, the EM 34-3 apparent conductivity is lower than the apparent conductivity of the EM 31, implying that less conductive material underlies the upper more conductive layer.

In the northern region, the prominent apparent conductivity lows of the EM 31 in the north central map area and along the eastern and western borders correlate with similar conductivity lows of the EM 34-3 map. However, in all cases the apparent conductivities of the EM 34-3 map are higher than those observed with the EM 31. This could indicate increased contribution from the till underlaying the surficial granular deposits. This increased contribution from the high conductivity till is counteracted to some extent by the contribution from the intertill granular material.

The narrow, nearly east-west striking conductivity low of the EM 31 map practically disappears on Drawings 3 and 4, confirming that its source is depth limited.

The areas of high apparent conductivity in the northeast and northwest corners persist on both maps, showing that the conductive till continues from near surface downwards.

The areas which were recommended for borehole testing are those where both maps exhibit conductivity lows. The zones where apparent conductivities are considerably lower than the background would have higher priority than those where the apparent conductivities are only slightly or marginally lower than the local background.

2.7/ Test Drilling

Test hole locations were selected by members of the study team and Messrs. Gruspier, Katona, and Barber of MTC at a meeting on October 31, 1985.

Messrs. McNeill and Jagodits felt that the area of coverage of the resistivity survey was sufficient and the test site selected was excellent as a wide range of conductivity readings were obtained for both the EM 31 and EM 34-3. Messrs. McNeill and Jagodits also speculated that the conductivity lows (resistivity highs) indicated granular material, which is likely more resistive than the lacustrine material.

It was agreed that test drilling should be conducted in a wide range of conductivity reading areas with particular emphasis on areas containing lows and highs. Grid lines F, N and S (see Dwg. No. 1) were identified as the optimum lines upon which to concentrate the majority of the test drilling as these lines intersected high, intermediate, and low readings. The test holes were spaced at approximately equal distances along these lines to facilitate preparation of soil profiles. The remaining test holes were located in areas of high and low readings throughout the test site.

Mr. Jagodits identified the locations for the test sites which should provide optimum data for interpretation. Mr. Katona requested that some testing be conducted in an area previously investigated by the Ministry of Natural Resources. In all, 31 test sites were selected.

Initially, test drilling and soil logging were conducted in December, 1985, and January, 1986 by MTC personnel, supervised by Mr. Barber, Mineral Aggregate Assessment Officer, Southwestern Region. Staff from Bird & Hale Limited were also at the site.

Representative samples of all soil types encountered were collected for laboratory analysis at a later date.

Extensive seams of gravel had not been located after drilling a substantial number of test holes. At that point, Mr. Katona of MTC was consulted to determine if and where additional test holes should be drilled. Three additional test holes were drilled in areas where gravel had been found during previous Ministry of Natural Resources test drilling surveys. This resulted in a total of 34 test sites.

The MTC test hole logs and laboratory analysis of soil samples are contained in Appendix D. The locations of all test holes and boreholes are indicated on Drawing No. 1. Explanations of soils abbreviations can be found in Appendix F.

2.8/ Analysis of Additional Data

During the course of the study, additional data were analysed to determine the geological history and soil characteristics of the study site and adjacent lands.

After the test drilling was completed, additional borehole logs for the study site were obtained from the Engineering and Terrain Geology Section, Ontario Geological Survey, Ministry of Natural Resources. These boreholes were logged by Messrs. E.V. Sado and C. Welsh and drilling was conducted in October, 1980, and June, 1981. These bore hole logs are contained in Appendix E and the locations are shown on Drawing No. 1. These logs have been incorporated into the report as they complement the results obtained during the MTC test drilling program.

Well logs were obtained from the Ministry of the Environment for the lands adjacent to the study site. Well logs were not available for the study site. These logs were analysed to determine the soil stratigraphy and static water table elevations in the region of the test site.

Information regarding the Quaternary and bedrock geology of the test site and surrounding areas was obtained from various documents and through consultation with geologists familiar with the area. These documents are listed in Appendix A; the information obtained is outlined in Section 3.1.

2.9/ Comparison of Inductive Resistivity Survey and Soils Data

2.9.1/ EM 31 Survey

The Surficial Granular Material Isopach Map has been combined with the EM 31 Conductivity Contour Map (see Dwg. No. 2). The isopach map represents the cumulative thickness of granular material (soils with a dominance of sands and gravels) above the first clay, silt, or till layer. The isopach contours have been developed by interpolating depths of surficial granular material between widely spaced boreholes (B.H.) and test holes (T.H.) located in certain areas of the test site. The maximum surficial granular material isopach contour is 6 m as this is the penetration depth of the EM 31.

The correlation between the surficial isopach contours and the EM 31 conductivity/contours is quite remarkable as increased thicknesses of surface granulars generally coincide with decreased apparent conductivity.

Test holes located in the southern region and in the northeast corner of the test site encountered nil or very little surface granular material, which is in keeping with the higher apparent conductivities observed in these areas. It is also interesting to note that B.H. 1, 3, 12 and 13 and T.H. 20 and 33 encountered less than 1 m of surficial granulars (east central map area) correlating with an area of higher apparent conductivity, where the conductivity reaches 30 mmho/m. The geophysical data imply that the area lacking surficial material extends towards the east, but this cannot be substantiated because the closest test holes are nearly 200 m away to the west.

A potential area of interest is in the north central map area where the conductivity decreases to 8 mmho/m, but T.H. 22 and B.H. 2 apparently encountered less than 1 m thickness of surface granular material. However, deeper sands were found here. It is important to note that the two anomalous (low conductivity) areas along the northern boundary and the anomalous zones along the east and the west boundary are open to the north, to the east and to the west, respectively.

2.9.2/ EM 34-3 Survey

Drawing 3 displays the EM 34-3 apparent conductivity contours and the buried granular material isopach contours.

The buried granular material isopach contours represent the cumulative thickness of granular-dominated materials below the first clay, silt or till layer. The isopach contours have been developed by interpolating the depths of buried granular material between boreholes and test holes.

Three areas of increased thickness of granular were noted:

- The first area is centred around B.H. 2 and it coincides with the north central conductivity low of about 12.5-13 mmho/m.
- The second area of increased thickness of granulars is located at about B.H. 4. In this area, the apparent conductivity is about 15 mmho/m. The correlation between the apparent conductivities and increased thicknesses in granular material in the above two situations is notable.
- The third area is found around B.H. 1 and 7. The apparent conductivities at both locations are slightly lower than the background apparent conductivities. This suggests that the electrical properties of the granulars are probably very similar to the electrical properties of the host materials. The total thickness of granular material is greater in B.H. 1, but it also includes layers of silt and clay. The log of B.H. 7 (Appendix E) shows that wet sand, clayey sand, silty sand and clay were also encountered. All these factors would explain the higher than expected apparent conductivities at these two localities.

Drawing 4 displays the total (buried and surficial) granular material isopach contours and the EM 34-3 apparent conductivity contours. The isopach contours represent the total cumulative depth of granular-dominated material and they have been interpolated from the soil log data at boreholes and test holes.

It is noted on Drawing 3 that areas containing deep granular materials generally coincide with areas of conductivity lows. However, when the surficial material is added to the buried material to produce the total granular material isopach contours, as on Drawing 4, the correlation between depth of granular material and EM 34-3 conductivity lows is less convincing because the contribution from the near-surface materials to the EM 34-3 apparent conductivity is small. Drawing 4 clearly illustrates the influence of the more conductive materials at depth on the EM 34-3 apparent conductivity.

Drawing 4 is useful in delineating the total areal extent of granular-dominated materials at the test site. It would also help in determining total volumes.

2.9.3/ Profiles Along Lines F, N, and S

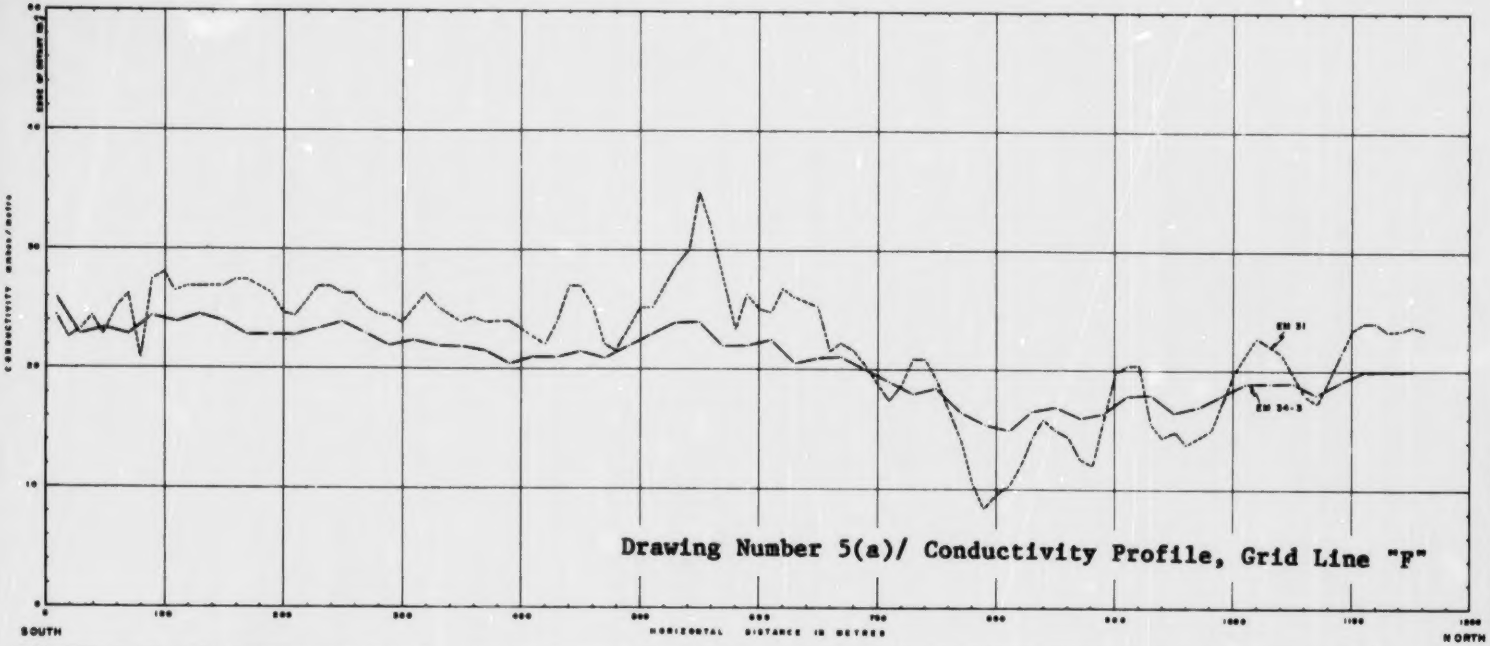
2.9.3.1/ General

The apparent conductivities observed with the two instruments, together with drilling results and topography are presented as profiles on Drawings 5a, 5b, 6a, 6b, 7a, and 7b. The correlation between the geoelectric data and drilling results is discussed below. It is noted here that when the apparent conductivities obtained with the two instruments are the same, it indicates that the electrical property of the ground is uniform down to the exploration depth of the deeper penetrating system. When the EM 31 apparent conductivity profile is above the EM 34-3 apparent conductivity profile, it generally means that higher conductivity material overlies the lower conductivity material. Conversely, if the EM 31 apparent conductivity profile is below the EM 34-3 apparent conductivity profile, it should indicate the presence of a lower conductivity upper layer.

2.9.3.2/ Profiles Along Line F (Drawings 5a and 5b)

From 0 to 600N the section is basically underlain by clays and silts, with an exception in T.H. 2. The conductivity of clays and silts is usually high and the survey results obtained here reflect this. The somewhat lower EM 34-3 apparent conductivities could indicate that more resistive materials may be present at depth. Silty sands were encountered in T.H. 2 and there is no apparent manifestation of this material in the conductivity data. The electrical properties of the silty sand are likely very close to the electrical properties of the underlying material, which explains the lack of geophysical response.

Between 700N and 1000N the EM 31 apparent conductivity decreases, indicating a resistive upper layer which correlates with the upper sand layer observed in T.H. 6 and 7. However, the geophysical data suggest that the upper sand layer does not occur at 900N where the EM 31 apparent conductivity increases measurably. Thus, the sand layer pinches out near 900N as shown on the drawing. The lower sand and silt layer in T.H. 6 probably caused the EM 34-3 apparent conductivity to reach its lowest level along this section. The apparent conductivities at T.H. 7 are about the same, indicating a nearly uniform half-space. This would



Drawing Number 5(a)/ Conductivity Profile, Grid Line "F"

Legend

EM 34-3
Operating horizontal dipole mode
Coil separation 20 m

EM 31
Operating vertical dipole mode
Reading taken at 10 m interval

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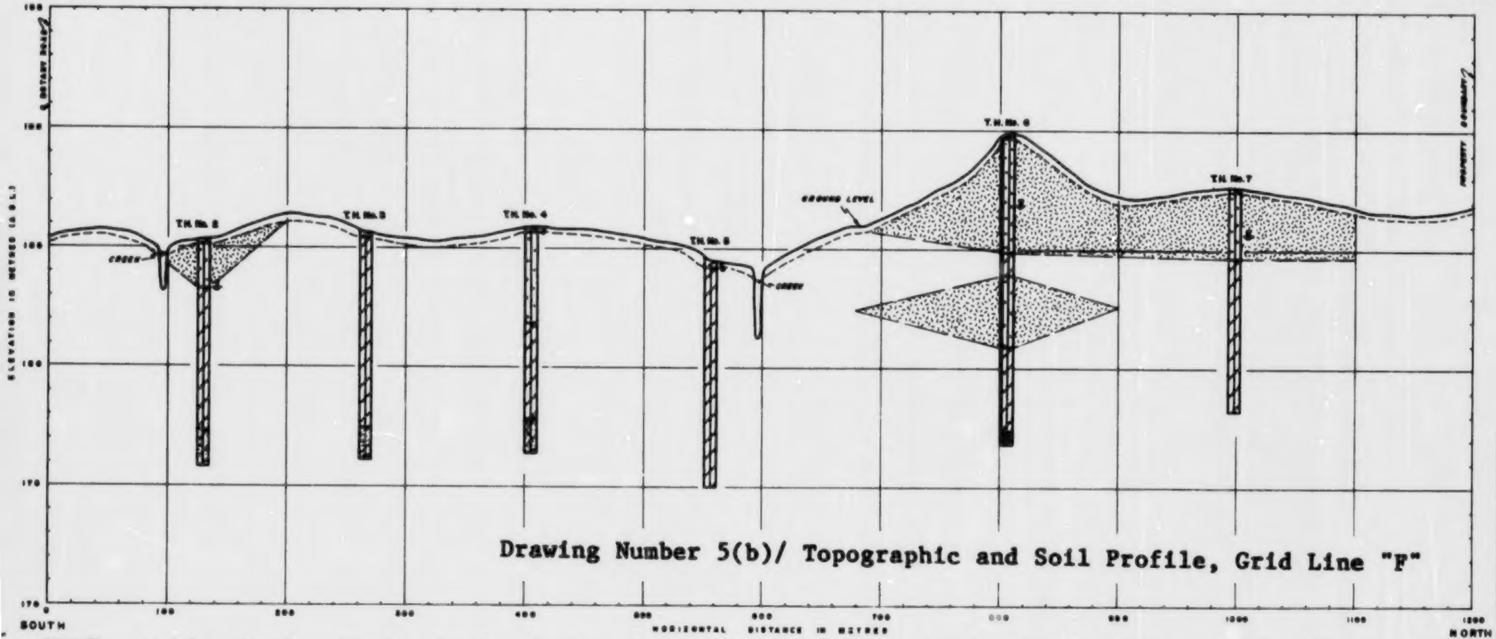
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS

CONDUCTIVITY PROFILE
GRID LINE 'F'

SCALE: HOR. 1 : 5000 VERT 1 : [illegible]
DATE: FEBRUARY, [illegible]
DRAWN: A.S.
CHECKED: W.R.H.
DRAWING No. 5a ([illegible])

bird and hale ltd.


ELEVATION IN METRES (G.S.L.)
ROTARY DRILL
T.H. No. 2
T.H. No. 3
T.H. No. 4
T.H. No. 5
T.H. No. 6
T.H. No. 7
CREEK
CREEK
GROUND LEVEL
PROPERTY BOUNDARY
SOUTH
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
NORTH
HORIZONTAL DISTANCE IN METRES

Drawing Number 5(b)/ Topographic and Soil Profile, Grid Line "F"

SOIL STRATA SYMBOLS

- ORGANICS or TOP SOIL
- GLACIAL TILLS (Cohesive)
- CLAYS
- CLAYS & SILTS
- SANDS
- SANDS & SILTS
- GRAVELS
- SANDS & GRAVELS
- SILTS
- WATER TABLE
- INDICATES ONE OR COMBINATION OF THE FOLLOWING: SANDS, SANDS & SILTS, GRAVELS, SANDS & GRAVELS

ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS

DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS

TOPOGRAPHIC AND SOIL PROFILE
GRID LINE 'F'

SCALE: HOR. 1 : 5000 VERT 1 : 100
DATE: FEBRUARY, [illegible]
DRAWN: A.S.
CHECKED: W.R.H.
DRAWING No. 5b ([illegible])

bird and hale ltd.

suggest that the silt content of the sand may have increased and, consequently, its conductivity is also increased. The electromagnetic resistivities do not appear to identify diagnostically the sand and silt horizon found at this test hole.

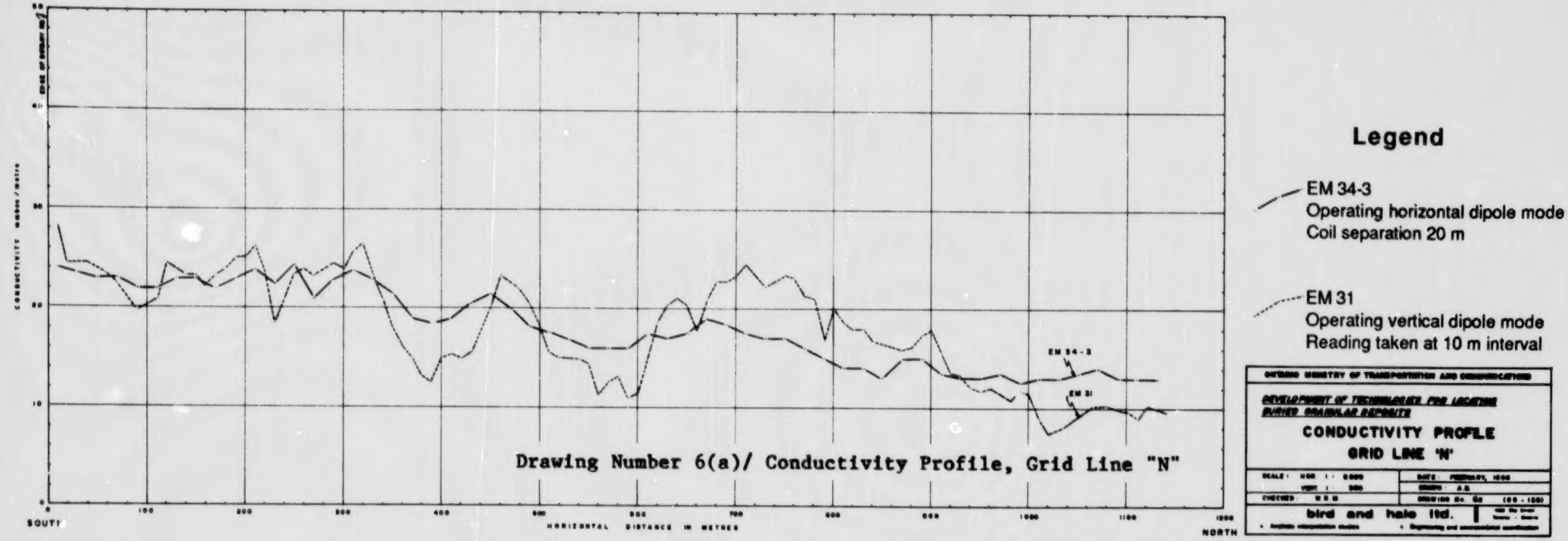
2.9.3.3/ Profiles Along Line N (Drawings 6a and 6b)

Conductive upper layer conditions are suggested by the profiles to about 330N, with minor exceptions. The average apparent conductivities indicate a thick clay and silt layer which is borne out in T.H. 17. From 330N to about 600N, both apparent conductivities decrease, excepting from 440N to 500N where conductive upper layer indications exist. The lower EM-31 apparent conductivities demark the upper sands, and sand and silts. The electromagnetic conductivities between 440N and 550N predict that the upper sand layer probably pinches out. B.H. 1 is about 30 m northeast of the line at 620 N and it intersected a thick section of sand and silts. This occurrence is not noted by the electromagnetic data, thus implying that the occurrence is likely very local and its conductivity may be higher because of the silt content. Furthermore, when the contribution from the somewhat higher conductivity sand and silt is combined with the contributions from high conductivity materials above it and below it, the resulting apparent conductivity can be quite high.

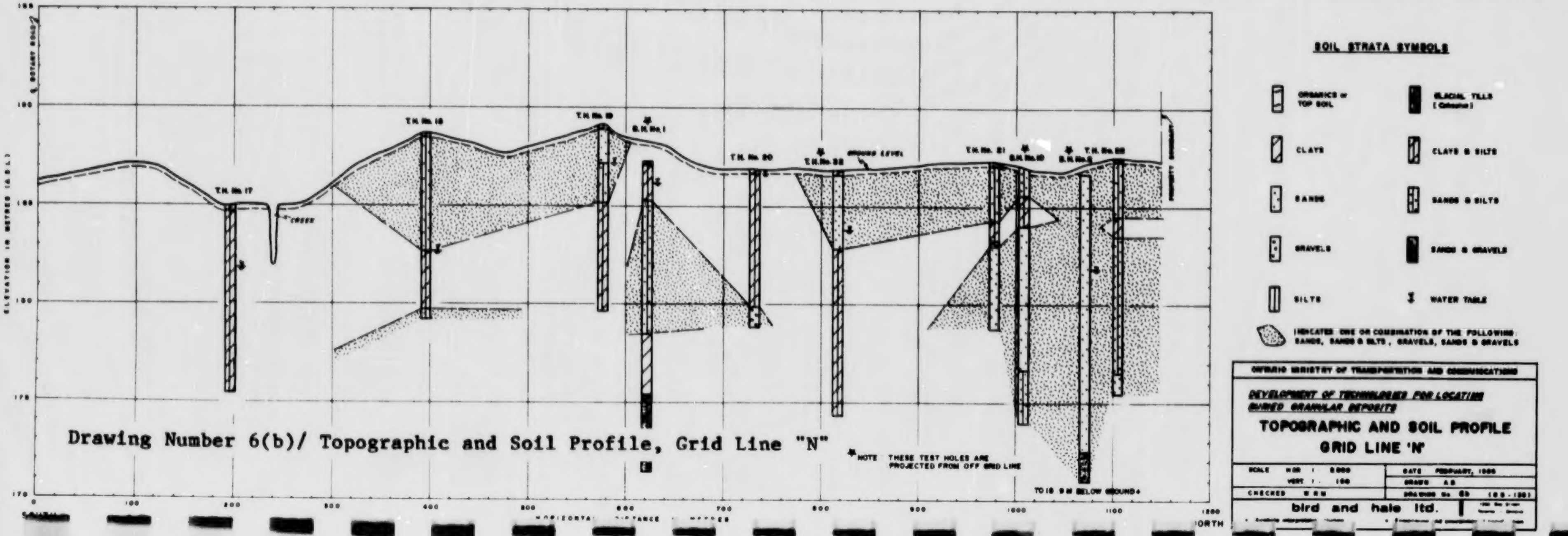
T.H. 20 at 730N encountered clays and silts in the upper 7 m. This would account for the higher EM 31 apparent conductivity. The lower EM 34-3 apparent conductivity could indicate the deeper more resistive layer.

The reconciliation between the apparent conductivities and the data of T.H. No. 32 is more difficult. The geophysical data indicate a more conductive upper layer. The first layer encountered by the drill hole is sands. It would appear that the true conductivity of the sand is higher than usual and when its contribution is combined with the contribution from the high conductivity underlying clay, the result will be a higher than expected EM 31 apparent conductivity. The decreasing EM 34-3 apparent conductivity suggests that less conductive material may exist below the termination depth of the test hole.

Just north of 900 N, both apparent resistivities attain their lowest levels. The drill results confirm the existence of thick sections of granular materials which is indicated by both apparent conductivities.



Drawing Number 6(a)/ Conductivity Profile, Grid Line "N"



Drawing Number 6(b)/ Topographic and Soil Profile, Grid Line "N"

ELEVATION IN METRES (A.S.L.)
T.H. No. 17
CREEK
T.H. No. 18
T.H. No. 19
B.H. No. 1
T.H. No. 20
T.H. No. 22
GROUND LEVEL
T.H. No. 21
B.H. No. 10
B.H. No. 9
T.H. No. 23
TO 18 9 M BELOW GROUND
NOTE THESE TEST HOLES ARE PROJECTED FROM OFF GRID LINE
SOUTH
NORTH
HORIZONTAL DISTANCE IN METRES
100
200
300
400
500
600
700
800
900
1000
1100
1200
SOIL STRATA SYMBOLS
ORGANICS or TOP SOIL
CLAYS
SANDS
GRAVELS
SILTS
GLACIAL TILLS (Cohesive)
CLAYS & SILTS
SANDS & SILTS
SANDS & GRAVELS
WATER TABLE
INDICATES ONE OR COMBINATION OF THE FOLLOWING: SANDS, SANDS & SILTS, GRAVELS, SANDS & GRAVELS
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS
TOPOGRAPHIC AND SOIL PROFILE
GRID LINE 'N'
SCALE HOR 1 : 5000
VERT 1 : 100
CHECKED
DATE FEBRUARY, 1986
DRAWN A.S.
DRAWING No. 6b
bird and hale ltd.

2.9.3.4/ Profiles Along Lines S (Drawings 7a and 7b)

T.H. 26, near 220N, penetrated some sands and silts, which shows excellent correlation with a narrow zone where the EM 31 apparent conductivities decrease sharply. The electromagnetic conductivity survey suggests that the sand-silt layer pinches out north of here and does not attain a reasonable thickness until T.H. 27, near 410N. The apparent conductivity data north of T.H. 27 to about 600N suggests that the sand-silt layer may be absent or its electrical properties are very similar to the electrical properties of the underlying clay-silt. The increased thickness of sand in T.H. 29 (690N) is clearly indicated by the lower EM 31 apparent conductivity, but the sand should pinch-out toward both the south and north of this test hole.

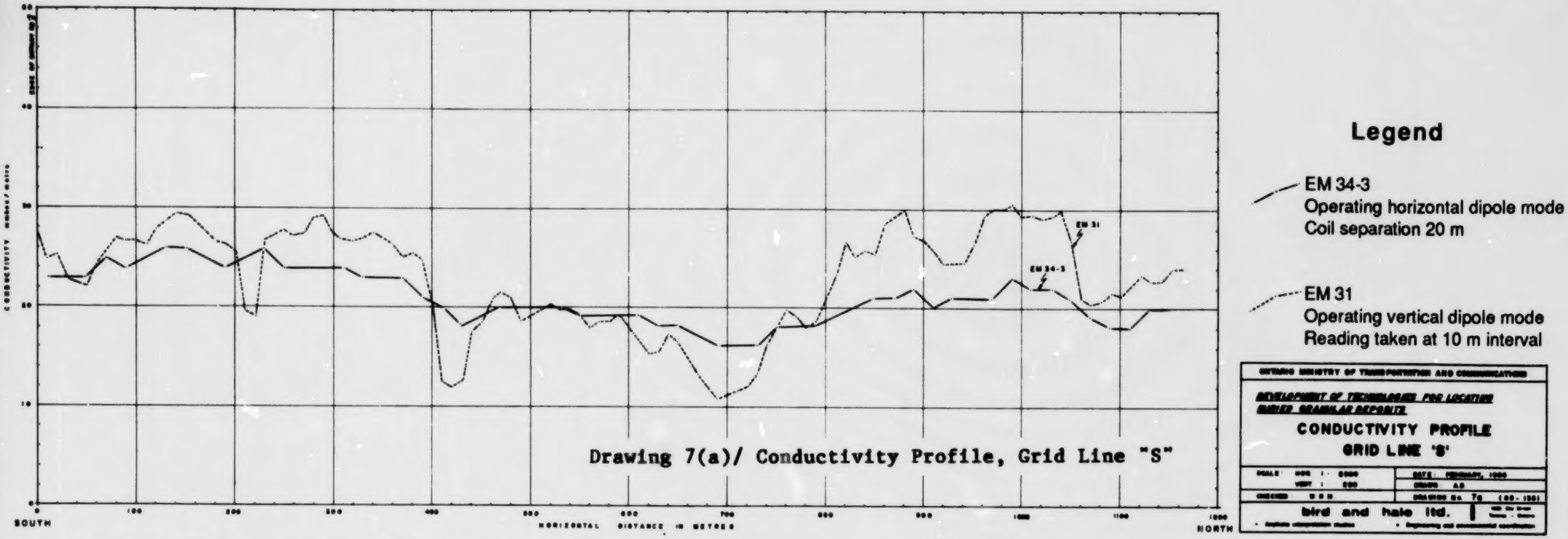
North of about 750N, the EM 31 apparent conductivity increases dramatically, signifying thick covering clays and silts as found in T.H. 30 and 31 (640N and 1030N, respectively). The lower EM 34-3 apparent conductivities could indicate deeper, less conductive material, as found at the bottom of both T.H. 30 and 31.

2.10/ Conventional Granular Investigation Methods

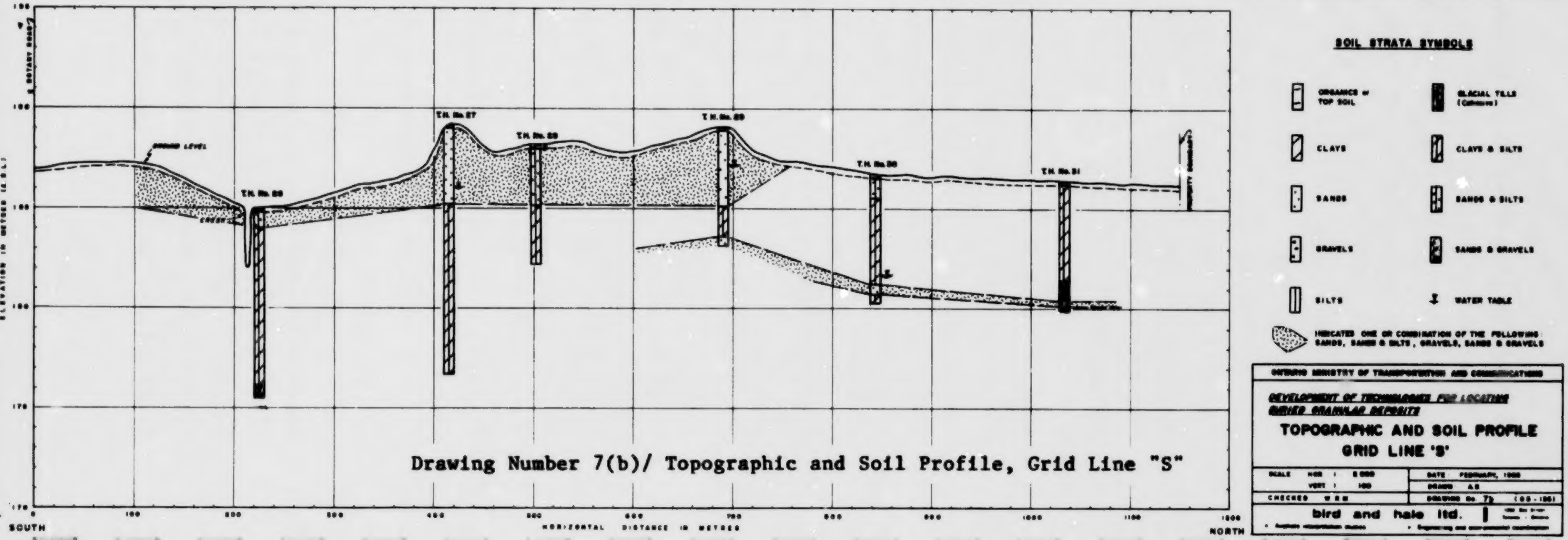
The conventional methods used for locating buried granular deposits include airphoto interpretation with selected field checking. Random boreholes in promising areas are also used.

Using airphoto interpretation, suspected areas of buried granular deposits are delineated. Subsequently, the soil strata at these locations are checked through field investigations. The difficulty associated with this method is that buried granular deposits often cannot be detected because of a lack of surface expression. The results of previous investigations have proven to be unreliable as the success rate of locating buried deposits has been relatively low.

Random boreholes have been drilled by government agencies such as the Ministry of Natural Resources in hopes of locating buried granular deposits. This is a very costly operation as granular deposits are rarely found. Even when they have been found, it has been very difficult to determine the configuration and extent of the deposits.



Drawing 7(a)/ Conductivity Profile, Grid Line "S"



Drawing Number 7(b)/ Topographic and Soil Profile, Grid Line "S"

ELEVATION IN METRES (A.S.L.)
SOUTH
NORTH
HORIZONTAL DISTANCE IN METRES
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
GROUND LEVEL
CREEK
T.H. No. 26
T.H. No. 27
T.H. No. 28
T.H. No. 29
T.H. No. 30
T.H. No. 31
SOIL STRATA SYMBOLS
ORGANICS or TOP SOIL
GLACIAL TILLS (Cohesive)
CLAYS
CLAYS & SILTS
SANDS
SANDS & SILTS
GRAVELS
SANDS & GRAVELS
SILTS
WATER TABLE
INDICATES ONE OR COMBINATION OF THE FOLLOWING: SANDS, SANDS & SILTS, GRAVELS, SANDS & GRAVELS
ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS
DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS
TOPOGRAPHIC AND SOIL PROFILE
GRID LINE 'S'
SCALE
DATE: FEBRUARY,
DRAWN: A.S
CHECKED
DRAWING No. 7b
bird and hale ltd.

3/ CONCLUSION

3.1/ Geology

3.1.1/ Bedrock Geology

The study site and surrounding environs are underlain by the Kettle Point Formation bedrock unit (Devonian). This is a distinctive black shale which is covered by approximately 25 m of unconsolidated material at the study site.

As the deepest test holes drilled were 12.5 m, this bedrock stratum was not intersected during the test program.

3.1.2/ Glacial Geology

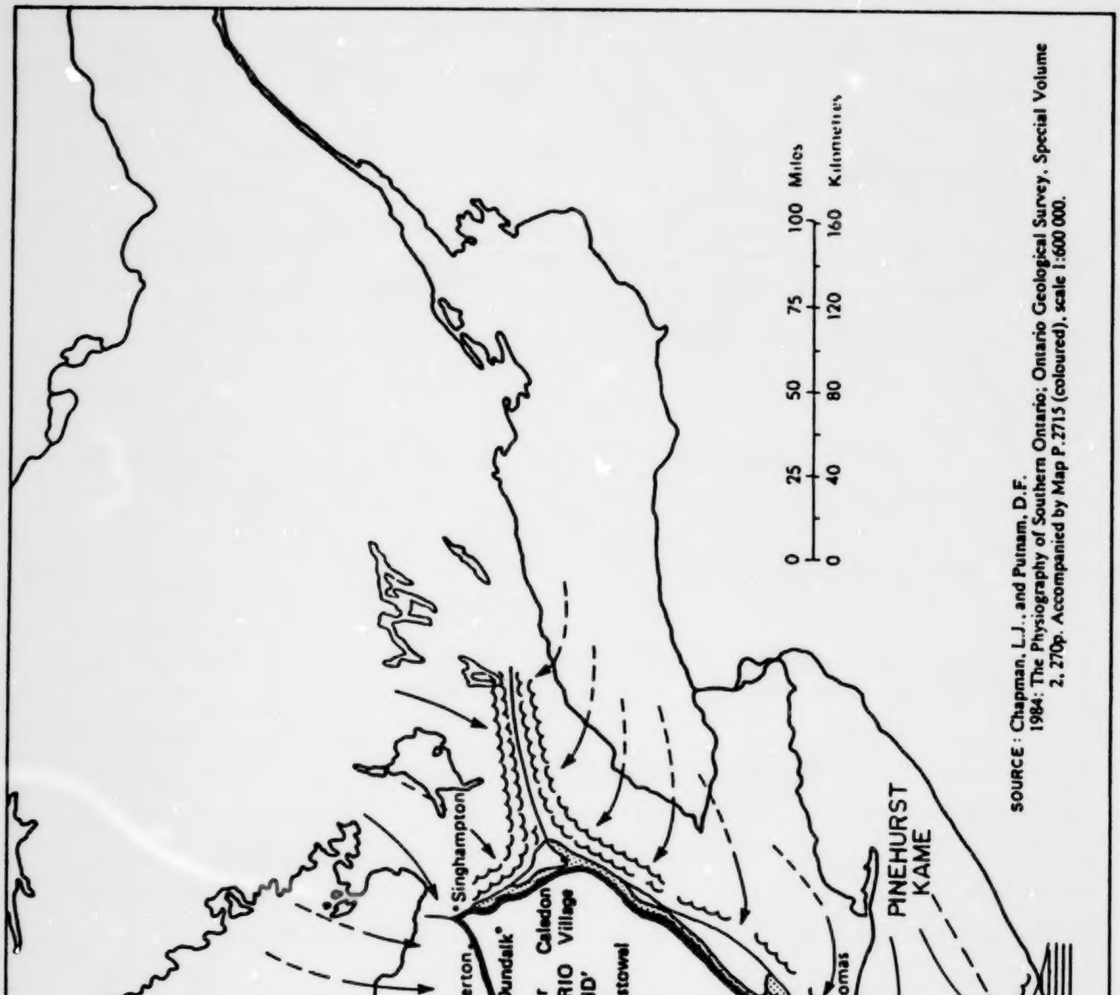
During the Wisconsinan glaciation, the site was located between the Huron and Ontario Erie ice lobes, as illustrated in Figure 3.1.

During periods of active glaciation, it appears that granular material was deposited as ice contact deposits. A possible illustration of this is the Pinehurst Kame (see Figure 3.1) where angular material has been deposited. Down drainage distributary channels cut into the previously deposited till and deposited outwash (sub-rounded material).

As the glacier receded, the area was inundated by numerous lakes, the most recent being Lake Warren. The site is below the elevation of the Lake Warren shoreline, the closest occurrence of which is 10 km southeast of the site. Therefore, the environment was primarily alternating energy lacustrine, resulting in strata of varying grain size. This is illustrated in Figure 3.2.

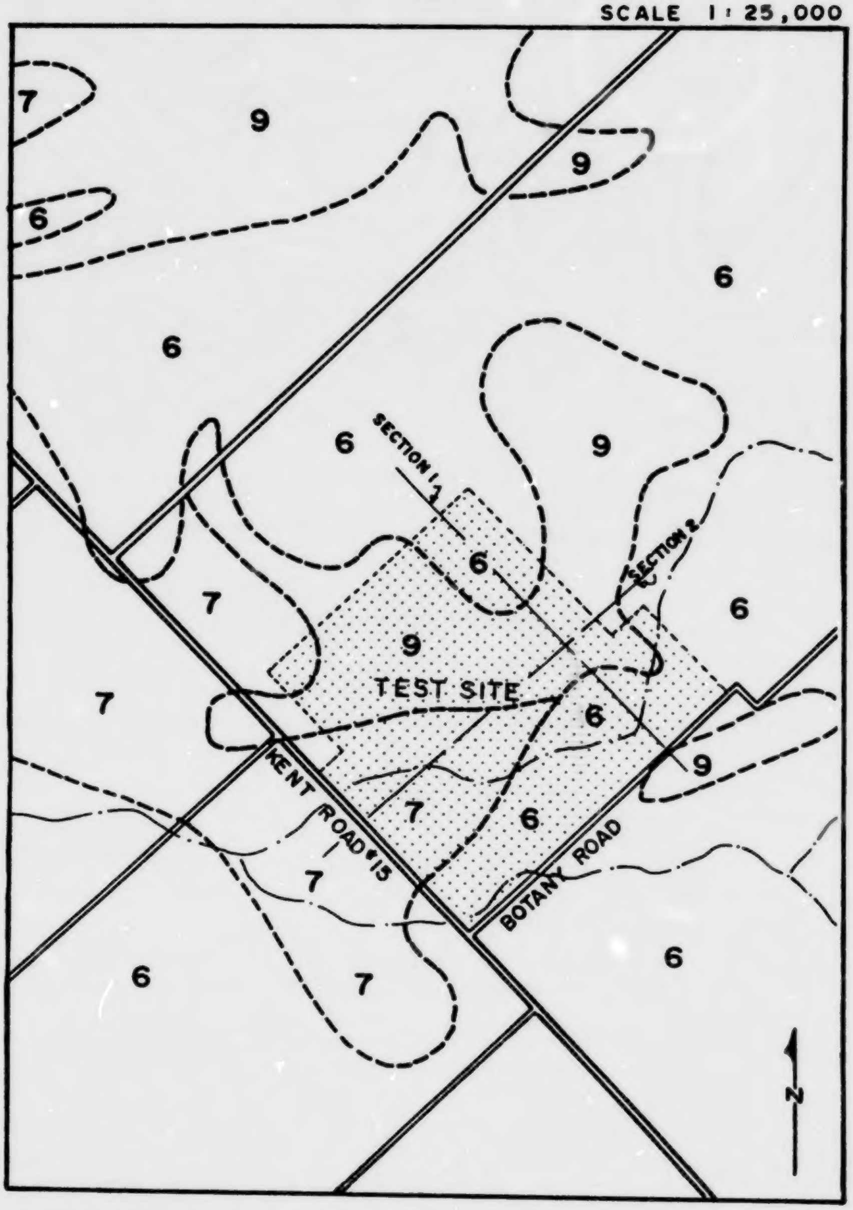
In the study area, it appears that buried granular material occurs primarily as discontinuous, sinuous strata. Generalized stratigraphic sections of the test site are shown on Figure 3.3. The stratigraphy of the test site was determined through evaluation of borehole data, water well logs, discussions with Ontario Geological Survey staff and data obtained from the Pinehurst deposit.

Overlaying the black shale bedrock is a discontinuous stratum of Huron or Ontario Erie till. This is a compact silty sand till with a thickness of approximately 7 m.


TEST SITE
via
Wabash River
LATE
LAKE
MAUMEE
London
St. Thomas
Seaforth
Teeswater
'ONTARIO
ISLAND'
Listowel
Flesherton
Dundalk
Caledon
Village
Singhampton
PINEHURST
KAME
0
25
50
75
100
Miles
0
40
80
120
160
Kilometres

SOURCE : Chapman, L.J., and Putnam, D.F.
1984: The Physiography of Southern Ontario; Ontario Geological Survey, Special Volume 2, 270p. Accompanied by Map P.2715 (coloured), scale 1:600 000.

Figure 3.1/ Recession of the Wisconsinan Glacier


SCALE 1:25,000
7
9
9
6
6
6
6
SECTION 1
9
SECTION 2
6
7
9
TEST SITE
7
6
9
KENT ROAD #15
7
6
BOTANY ROAD
7
6
7
6
N

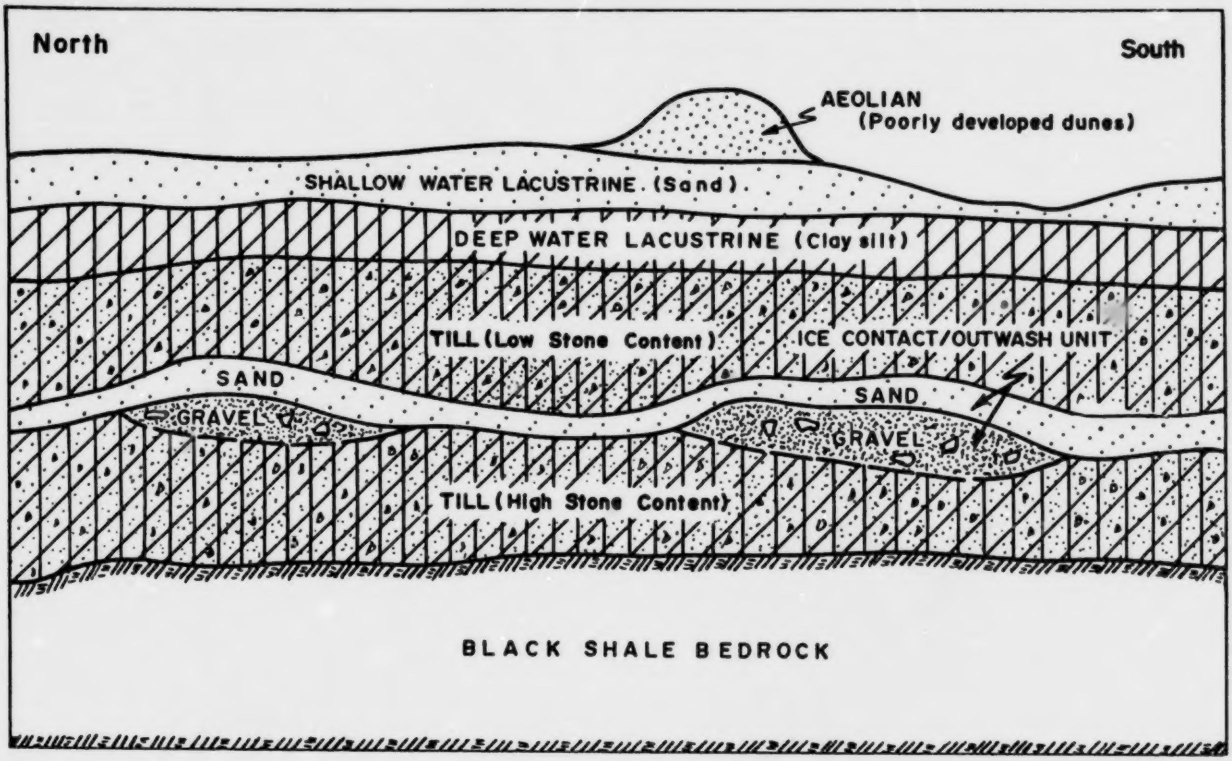
RECENT ENVIRONMENT

6	ALTERNATING ENERGY ENVIRONMENT - SILTY CLAY AND SILTY FINE SAND BANDS, SOME SHELLS PRESENT
7	HIGHER ENERGY ENVIRONMENT - SILTY FINE SAND TO MEDIUM SAND WITH SILT LENSES COMMON, SHELLS PRESENT MAY INCLUDE FLUVIAL SEDIMENTS AND SHALLOW WATER LACUSTRINE SEDIMENTS
9	EOLIAN DEPOSITS - FINE TO MEDIUM SAND FREQUENTLY FORMING DUNES

SOURCE: SADO, E.V, IN PREPARATION. QUATERNARY GEOLOGY OF THE CHATHAM AREA, PRELIMINARY MAP. ONTARIO GEOLOGICAL SURVEY

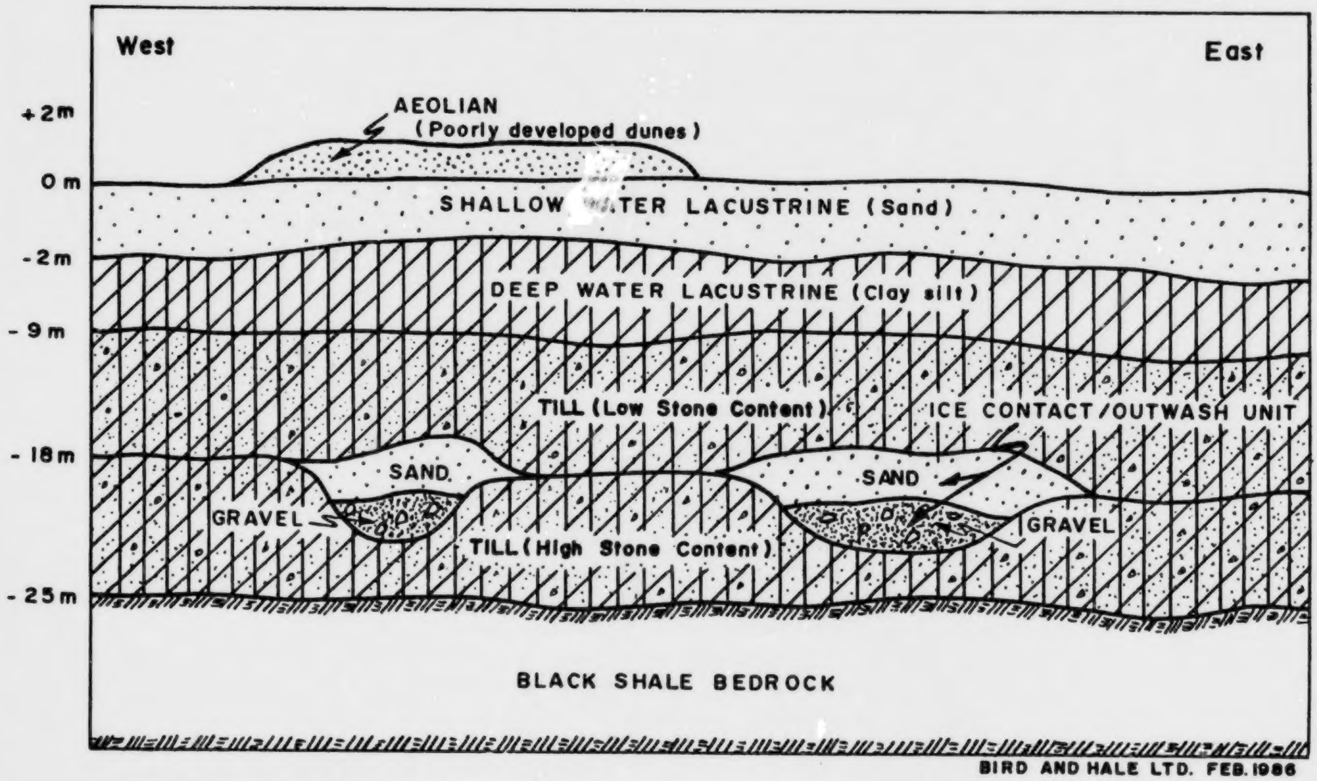
Figure 3.2/ Quarternary Geology of the Test Site

Section 1


North
South
AEOLIAN
(Poorly developed dunes)
SHALLOW WATER LACUSTRINE (Sand)
DEEP WATER LACUSTRINE (Clay silt)
TILL (Low Stone Content)
ICE CONTACT/OUTWASH UNIT
SAND
GRAVEL
SAND
GRAVEL
TILL (High Stone Content)
BLACK SHALE BEDROCK

Section 2

NOT TO SCALE


West
East
+2m
0 m
-2m
-9 m
-18m
-25m
AEOLIAN
(Poorly developed dunes)
SHALLOW WATER LACUSTRINE (Sand)
DEEP WATER LACUSTRINE (Clay silt)
TILL (Low Stone Content)
ICE CONTACT/OUTWASH UNIT
SAND
SAND
GRAVEL
GRAVEL
TILL (High Stone Content)
BLACK SHALE BEDROCK

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Note: Section 2 perpendicular to Section 1.

Descriptions of stratigraphic units on following page; Thicknesses discussed in text

SOURCE: MODIFIED FROM SADO, E.V., n.d.

Figure 3.3/ Generalized Stratigraphic Sections of the Test Site

Above the till is a discontinuous stratum of well washed and sorted sand and gravels deposited as ice contact or outwash. The thickness of this stratum is highly variable from 0.25 m to 10 m.

Overlaying the sand and gravel is till which is composed of silt, clay, some sand, and occasional fine gravel. The till has an average thickness of 9 m.

A 7 m (average) stratum of thinly bedded deep water lacustrine clayey silts and silty clays is situated above the till. Above this, is a stratum of shallow water lacustrine material consisting of thinly bedded silty fine to medium sand with an average thickness of 2.5 to 3 m.

Finally, a discontinuous stratum of poorly developed dunes consisting of fine to medium grained aeolian sand, occurs on the surface of the site.

As indicated above, the geology of the test site is relatively complex. This was confirmed by the nature of the resistivity readings. Interpretation of these readings assisted greatly in understanding the glacial geology of the test site.

3.2/ Granular Material Resources

The granular samples obtained during the test drilling were analysed in the MTC laboratory. The results were checked against the Ministry's gradation limits for granular "A", granular "B", granular "C" and asphalt sand, as shown in Appendix G. Only sample No. 85AO 2028, obtained from test hole 34, was acceptable as granular "C" material. Other samples obtained from test holes 23 and 34 could meet the specifications of granular "B" or "C" if they were processed to remove the excess fines. A typical processing method used is washing.

Some of the Ministry of Natural Resources boreholes also contained granular material but no samples were available for analysis to determine their acceptability for standard granular usage.

Since the granular material was not acceptable in situ and the deposits are relatively small, localized and discontinuous, it is likely not economical to mine these materials. Therefore, no attempt has been made at this point to estimate the quantities of granular materials available.

3.3/ Inductive Resistivity Surveys

The inductive electromagnetic surveys successfully outlined the areas of granular material potential and the surveys also eliminated zones where the probability of finding granular deposits is very low.

The detailed electromagnetic terrain conductivity surveys have delineated two regions of differing electrical properties within the test site. Throughout the majority of the southern half of the test site, relatively high apparent conductivities were observed with both instruments, indicating that the bedrock is overlain by conductive clays, tills and sandy silts. The EM 31 apparent conductivity contour map shows that, within restricted areas, thin layers of less conductive materials in the form of surface sands probably occur. Nevertheless, this area can be considered as lacking granular material potential. This interpretation was corroborated by the findings of the test drilling.

In the northern half of the test site, lower EM 31 apparent conductivities prevail, denoting that less conductive surface materials (sand, silty sands) are more common. Furthermore, lower apparent conductivities obtained by the EM 34-3 predict deeper and/or thicker granular materials. Both observations are substantiated to a large extent by the drilling results.

In addition to outlining areas of granular material potentials (the primary purpose of the survey), the data have also contributed to the understanding of the Quaternary geology of the area, which was assumed to be fairly complex. Apparent conductivity data indicate the thickness and depth of the intertill granular material can be quite variable. The results obtained with the shallower penetrating EM 31 instrument portray a discontinuous, less conductive, upper layer which is sand and silty sand. The detailed correlation of soil and conductivity data along three lines (F, N, and S) shows that the conductivity data, in the vast majority of cases, represent the variations in the types of unconsolidated earth materials within the exploration depths of the instruments used.

The above considerations lead to the following final conclusions regarding electromagnetic terrain conductivity surveys (inductive resistivity surveys). The method can be used:

1/ to delineate areas with granular material potential;

2/ to quickly eliminate areas where further work likely would be useless;

3/ to interpolate the Quaternary geology between drill holes; and,

4/ cost-effectively, particularly by delineating large areas and by cutting down on the number of drill holes necessary for this delineation.

3.4/ Conventional Granular Investigation Methods

Airphoto interpretation of the test site was carried out in the early stages of the study. It was possible to delineate the surficial deposits of sand; however, the buried granular deposits were not detected due to a lack of surface expression.

Random test holes were drilled at the test site by the Engineering and Terrain Geology Section, Ontario Geological Survey, Ministry of Natural Resources, in October, 1980, and June, 1981. This test hole survey yielded a relatively high success rate in locating buried granular deposits. For this test site it was not possible to determine the extent of the deposits using the drilling method because of the discontinuous nature and variable thickness of the deposit. Therefore, drilling results cannot be relied upon to show the full extent and configuration of deposits of this type.

In order to obtain reliable results under such conditions, a test hole survey grid must be established with test holes drilled at a regular interval (for example, at 50 or 60 m over suspected granular deposits). This would be extremely expensive because of the number of test holes required. In the case of thick continuous deposits, the borehole data would be more reliable in delineating the approximate extent of the deposits; however, to obtain a more accurate mapping of the deposit, it would still be necessary to conduct a test hole survey at a grid spacing of 75 to 100 m, depending on the size of the deposit. It should be noted that the relatively high success rate realized in the Ministry of Natural Resources test hole survey is not the norm. Experience has shown that random test hole surveys are unsuccessful in locating buried granular deposits in the majority of cases.

In summary, random borehole surveys are expensive to perform, they may not detect granular material, and the extent and configuration of any granular material that is detected cannot be determined without digging or drilling a large number of test holes. Airphoto interpretation and selected field checking is relatively inexpensive; however, it is often not possible to detect buried granular deposits.

Resistivity surveys, on the other hand, can be performed economically by a two-man crew, producing reliable results that may be used to delineate buried granular deposits quite accurately.

3.5/ Limitations of the Resistivity Method

The results of the test drilling program on this project have illustrated the usefulness of the resistivity method in locating buried granular deposits. However, this only applies if the silt and water content of the granular material is relatively low. In areas where these parameters are relatively high, the apparent conductivity is higher than that which would normally be expected for granular material. Therefore, in such areas, it is more difficult to detect the presence of granular material from the apparent conductivity data obtained.

With reference to Drawing 2, the following examples illustrate the preceding points:

1/ Test hole 1 contains 2.8 m of surficial very fine silty sand, but an unusually high apparent conductivity reading of 37 mmho/m was recorded when using the EM 31. Although a sample was not analysed, it is reasonable to assume that the silt content of this material is relatively high, causing the high apparent conductivity.

2/ Test hole 28 contains 2.8 m of wet surficial fine to very fine sand. However, the apparent conductivity reading recorded when using the EM 31 was moderate at 20 mmho/m. The higher apparent conductivity is due to the relatively high moisture content of 24.0%.

4/ RECOMMENDATIONS

It is recommended that test lines should be surveyed with the EM 31 and EM 34-3, or similar electromagnetic terrain conductivity measuring instruments, over the Pinehurst deposit located southwest of the test site, in order to determine conductivities associated with an established buried granular deposit. The conductivity readings obtained would likely be lower than those obtained during this study, due to the more granular characteristics of the soil. The survey would provide benchmark data which could be used when evaluating terrain conductivities which are obtained under the same general geolcgical conditions. The survey would also permit delineation of the extent and thickness of the Pinehurst deposit, and contribute to further understanding of the Quarternary geology of the area, possibly resulting in identification of potential deposits.

It is also suggested that three survey lines from this study (F, N, S) should be surveyed again using a coil separation of 20 m and the vertical co-planar dipole coil configuration. This would yield results to a depth of 30 m. Then, these lines should be surveyed using a coil separation of 40 m, with observations being made at both coil configurations (horizontal and vertical dipole). The horizontal dipole configuration would allow readings to be taken to a depth of 30 m, while the vertical dipole configuration would yield results to a depth of 60 m. The additional data would also illustrate the variations of the apparent conductivity with depth. The conductivities obtained from greater depths may be useful in delineating those areas of buried granular deposits which continue to depths below 15 m and were not detected because they were located below the sensing depth (15 m) of the EM 34-3 as it was configured for the original survey. The possibility of this condition occurring is apparent from the data obtained at B.H. 2, where granular material was found to a depth of at least 18.9 m.

The results of the additional work would complete the suite of electromagnetic conductivities which then can be used to compute thicknesses and true conductivities to be compared with the geologic data from drilling.

The test surveys clearly indicated the usefulness of the method for locating granular material, providing that the inherent limitations imposed by the method are recognized. In order to encourage the use of the method, it would be most advantageous to organize seminars for field personnel to acquaint them with the principles of the method, instruments, survey techniques, limitations and the preliminary evaluation of the survey data.

ACKNOWLEDGEMENTS

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- Mr. Z.L. Katona, Senior Soils and Aggregate Engineer and technical advisor.

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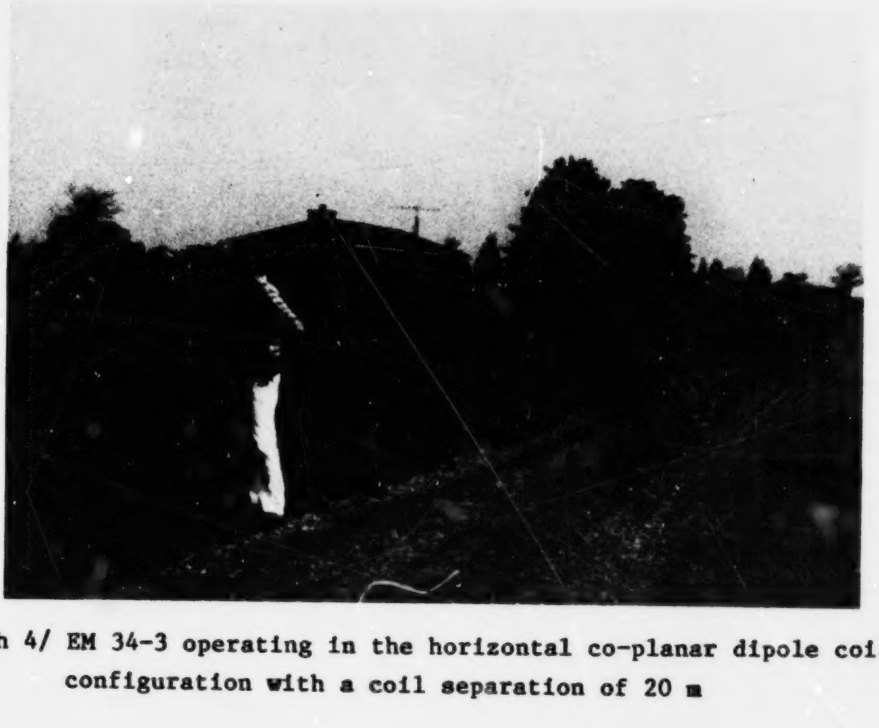
APPENDIX A

GROUND PHOTOGRAPHS

Photograph 1/ EM 31 in operating mode with analogue recorder connected.
Note: Instrument is operating in vertical dipole (normal) mode.

Photograph 2/ EM 31 folded down (non-operative mode).

Photograph 3/ EM 34-3 receiver



Photograph 4/ EM 34-3 operating in the horizontal co-planar dipole coil configuration with a coil separation of 20 m

Photograph 5/ MTC mobile flight auger drill in operation during the test drilling program.

APPENDIX B

Technical Note TN-6

ELECTROMAGNETIC TERRAIN CONDUCTIVITY MEASUREMENT AT LOW INDUCTION NUMBERS

(Source: McNeill, J.D., 1980. Geonics Ltd.)

I. INTRODUCTION

The measurement of terrain resistivity to map geology has been utilized for over half a century. Several shortcomings, however, have prevented this technique from being widely accepted for engineering purposes. The first of these is that conventional galvanic resistivity surveys require a relatively large amount of manpower to execute and are thus expensive. Secondly, the actual value of resistivity itself is seldom diagnostic; it is the lateral or vertical variations of resistivity which form the basis of any interpretation. However the high cost of resistivity surveying generally means that fewer measurements are made than would be desirable, with the result that either (i) the survey area is not made large enough to establish a reasonable background against which the anomalous areas are to be delineated or (ii) the anomalous area itself is obscure and lacks definition.

An additional problem inherent to conventional resistivity techniques is that although the effective depth of exploration is determined by the selected inter-electrode spacing, resistive inhomogeneities which are small compared to this depth but which are located near the potential electrodes can cause a significant error in the measurement. Such fluctuations in the measured results are truly geological "noise" because it is not possible to determine the physical size, resistivity contrast, or location of the source. As a result of such inhomogeneities resistivity profiles carried out at constant interelectrode spacing tend to be noisy, limiting the resolution in resistivity that can be achieved, even though the instrumentation itself is capable of producing much higher accuracy.

It was an awareness of both the advantages of resistivity for engineering geophysical surveys and the disadvantages of conventional resistivity techniques that led Geonics Limited to examine the possibility of employing electromagnetic (inductive) techniques as an alternative for resistivity surveys. With the development of the EM31 and the EM34-3 it is now possible to map terrain conductivity virtually as fast as the operator(s) can walk; furthermore the sample volume is averaged in such a manner as to yield unexcelled resolution in conductivity.

These patented instruments have been designed to cover the range of depths generally useful for engineering geophysics; the EM31, one-man portable, has an effective depth of approximately 6 meters and the EM34-3, two-man portable, has stepwise selectable depths from 7.5 meters to a maximum of 60 meters.

Typical applications for the EM31 and EM34-3 instrumentation are:

(i) Delineating regions of permafrost (frozen pore water)
(ii) Locating gravel
(iii) Extending known gravel deposits
(iv) Mapping saline intrusions
(v) Detecting cavities in carbonate rocks
(vi) Mapping pollution plumes in groundwater
(vii) Mapped bedrock topography
(viii) Mapping terrain conductivity for electrical grounding
(ix) General geological mapping (soil types, fault and fracture zones, etc.)
(x) Archaeological exploration
(xi) Locating pipes (EM31) and metallic-type conductors

This technical note describes both the principles and the instrumentation employed to measure terrain conductivity using electromagnetic techniques at low induction numbers. For a detailed discussion of the concept of terrain resistivity/conductivity and of the various factors that control this parameter the reader is referred to Geonics Limited Technical Note "Electrical Conductivity of Soils and Rocks".

II. PRINCIPLE OF OPERATION

The application of electromagnetic techniques to the measurement of terrain resistivity, or more properly, conductivity* is not new and excellent descriptions of this technique are given in the literature [1], [2].

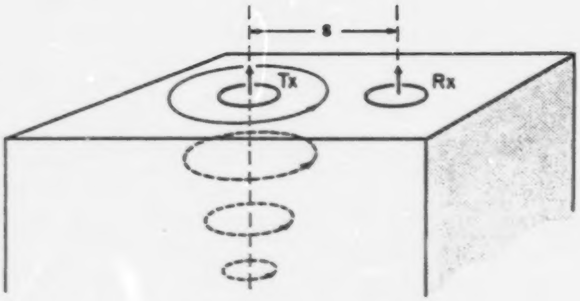


FIGURE 1. Induced current flow (homogeneous halfspace).

Consider Figure 1 in which a transmitter coil Tx energized with an alternating current at an audio frequency, is placed on the earth (assumed uniform) and a receiver coil Rx is located a short distance s away. The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field H_s which is sensed, together with the primary field, H_p, by the receiver coil.

In general this secondary magnetic field is a complicated function of the intercoil spacing s, the operating frequency, f, and the ground conductivity σ. Under certain constraints, technically defined as "operation at low values of induction number" (and discussed in detail in the appendix) the secondary magnetic field is a very simple function of these variables. These constraints are incorporated in the design of the EM31 and EM34-3 whence the secondary magnetic field is shown to be:

$$\frac{H_s}{H_p} \simeq \frac{i\omega\mu_0\sigma s^2}{4} \qquad (1)$$

where H_s = secondary magnetic field at the receiver coil
H_p = primary magnetic field at the receiver coil
$\omega = 2\pi f$
f = frequency (Hz)
μ_0 = permeability of free space
σ = ground conductivity (mho/m)
s = intercoil spacing (m)
$i = \sqrt{-1}$

The ratio of the secondary to the primary magnetic field is now linearly proportional to the terrain conductivity, a fact which makes it possible to construct a direct-reading, linear terrain conductivity meter by simply measuring this ratio. Given H_s/H_p the apparent conductivity indicated by the instrument is defined from equation (1) as

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right) \qquad (2)$$

The MKS units of conductivity are the mho (Siemen) per meter or, more conveniently, the millimho per meter.

III. INSTRUMENTATION

The EM31 (shown in Figure 2) has an intercoil spacing of 3.7 meters, which yields an effective depth of exploration of about 6 meters. The instrument can also be operated on its side, in which

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*Conductivity is preferred with inductive techniques since the response is generally proportional to conductivity and inversely proportional to resistivity.

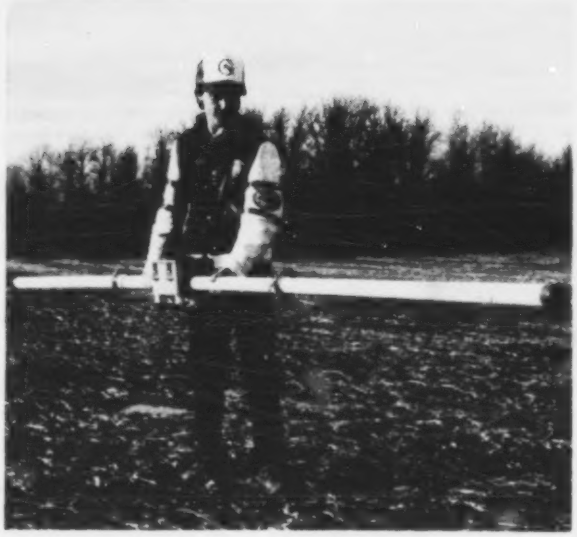


FIGURE 2. EM31 in field operation.

case as will be seen in Section IV., the effective depth of exploration is reduced to approximately 3 meters. The instrument is one-man portable and can be used either in "station-by-station" mode or read continuously. The presence of layering in the earth can be detected by raising the instrument and noting the readings as a function of instrument height. If the earth is two-layered the conductivity of both layers and the upper layer thickness can be resolved.

The EM34-3 which is two-man portable has the two coils flexibly connected (Figure 3). The intercoil spacing is measured electronically so that the receiver operator simply reads a meter to accurately set the coils to the correct spacing, which can be 10, 20, or 40 meters so as to directly vary the effective depth of exploration as shown in Table 1.

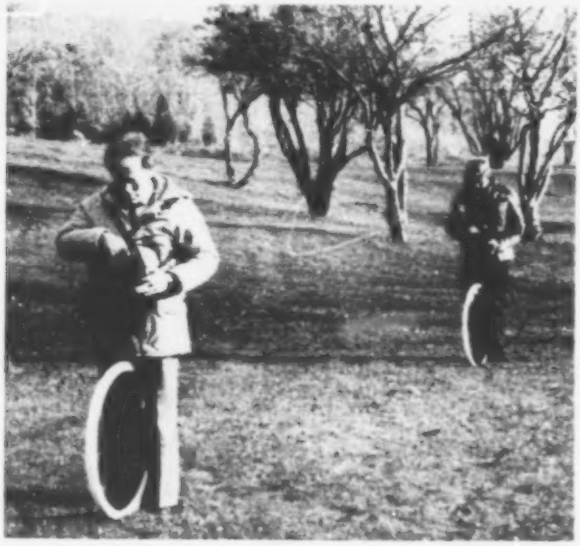


FIGURE 3. EM34-3 in field operation.

TABLE 1. Exploration depths for EM34-3 at various intercoil spacings

Intercoil Spacing (meters)	Exploration Depth (meters)	
	Horizontal Dipoles	Vertical Dipoles
10	7.5	15
20	15	30
40	30	60

To measure terrain conductivity the transmitter operator stops at the measurement station; the receiver operator moves the receiver coil backwards or forwards until his meter indicates correct intercoil spacing and he reads the terrain conductivity from a second meter. The procedure takes 10 to 20 seconds. The coils are normally carried with their planes vertical (horizontal dipole mode) since in this configuration the measurement is relatively insensitive to misalignment of the coils. In the event that the greater depth of penetration resulting when the two coils are in the vertical dipole mode is desired, more care must be taken with intercoil alignment. Because of the relatively short intercoil spacing correct alignment is usually not difficult to achieve.

Both instruments are calibrated to read terrain conductivity in millimhos per meter. To convert these readings to resistivity (in ohmmeters) one simply divides them into 1,000, i.e. 50 millimhos per meter is the equivalent of 20 ohmmeters.

IV. SURVEY TECHNIQUES AND INTERPRETATION

For either the EM31 or EM34-3 it can be shown that in a homogeneous or horizontally stratified earth the current flow is entirely horizontal. Furthermore under the constraints by which the instruments are designed the current flow at any point in the ground is independent of the current flow at any other point since the magnetic coupling between all current loops is negligible. Finally, under these constraints the depth of penetration is limited only by the intercoil spacing. We say that the depth of penetration is "source" or "geometry" limited rather than "skin depth" limited since it is now controlled by the fall-off with distance of the dipolar transmitter field. For this reason all dimensions are normalized with respect to the intercoil spacing in subsequent sections of this technical note.

IV. 1. Instrumental Response as a Function of Depth (Homogeneous Halfspace)

Consider a homogeneous halfspace on the surface of which is located an EM31 or an EM34-3 transmitter as shown in Figure 4. Fixing our attention on a thin layer of thickness dz at depth z (where z is the depth divided by the intercoil spacing s) it is possible to calculate the secondary magnetic field in the receiver coil arising from all of the current flow within this or any other horizontal thin layer. One can thus construct the function $\phi_V(z)$ shown in Figure 4 which describes the relative contribution to the secondary magnetic field arising from a thin layer at any depth z. We see from this figure that material located at a depth of approximately 0.4 s gives maximum contribution to the secondary magnetic field but that material at a depth of 1.5 s still contributes significantly. It is interesting to note that the ground at zero depth, i.e. the near surface material,

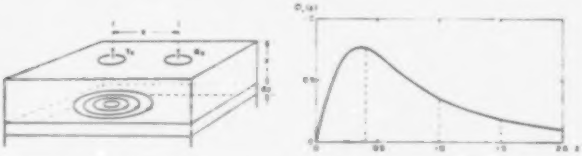


FIGURE 4. Relative response versus depth for vertical dipoles. $\phi_V(z)$ is the relative contribution to H_s from material in a thin layer dz located at (normalized) depth z.

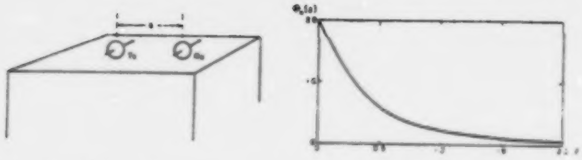


FIGURE 5. Relative response versus depth for horizontal dipoles

makes a very small contribution to the secondary magnetic field and therefore this coil configuration is insensitive to changes in near surface conductivity.

Figure 5 illustrates the function of Figure 4 for the case of both transmitter and receiver dipoles horizontal coplanar rather than vertical coplanar. For the coil configuration of Figure 5 (commonly used for the EM34-3 since it is less critical to intercoil alignment) the relative contribution from material near-surface is large and the response falls off monotonically with depth.

A comparison of the function ϕ for both coil configurations in Figure 6 emphasizes the different manner in which they respond to material at different depths. The difference is important since either instrument can be rolled over so that the vertical dipole transmitter/receiver geometry becomes a horizontal dipole transmitter/receiver geometry and vice versa. As will be seen later, this feature is useful in diagnosing and defining a layered earth. The figure also shows that for regions greater than one intercoil spacing in depth the vertical transmitter/receiver dipole gives approximately twice the relative contribution of the horizontal transmitter/receiver dipole.

To summarize, with either horizontal or vertical transmitter/receiver dipole orientation it is possible to construct a function which gives the relative response to the secondary magnetic field at the receiver from a thin layer of ground at any depth. That this is possible arises from the fact that (i) all current flow is horizontal and (ii) all current loops are independent of all other current loops. It should be noted that it is not possible to construct such functions for conventional resistivity techniques.

Finally, since as shown in Section II the definition of apparent conductivity is given in terms of the secondary magnetic field at the receiver, the functions in Figure 6 also give the relative contribution from material at different depths to the *apparent conductivity* indicated by the instrument meter. The integral of either function from zero to infinity gives the total secondary magnetic field at the receiver coil from a homogeneous halfspace which is directly related to the electrical conductivity of the halfspace by equation (1). It is therefore possible to state with great precision the relative influence of material at different depths to the indicated apparent conductivity.

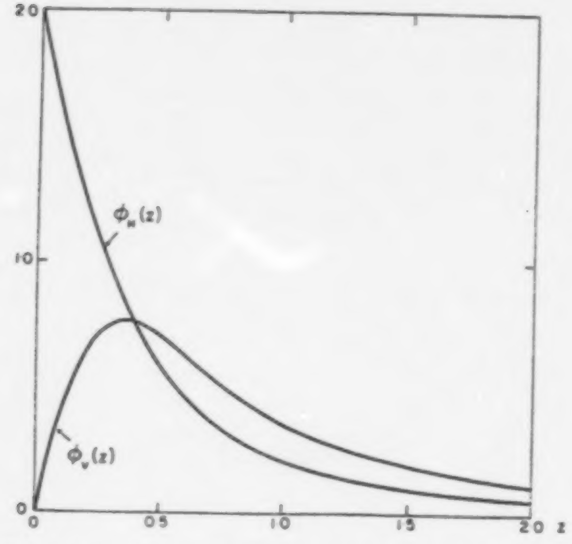


FIGURE 6. Comparison of relative responses for vertical and horizontal dipoles.

IV. 2. Multi-Layered Earth Response

The functions shown in Figure 6 are useful for describing the relative sensitivity of either of the two coil configurations to material at various depths. However a function derived from them is more useful for performing calculations. It is defined as the relative contribution to the secondary magnetic field or apparent conductivity from all material below a depth z and is given by

$$R_{\substack{V\\H}}(z) = \int_z^\infty \phi_{\substack{V\\H}}(z)dz \qquad (3)$$

Called the cumulative response, this function is illustrated in Figure 7 for vertical coplanar transmitter/receiver dipoles. The figure shows, for example, that for this configuration all material below a depth of two intercoil spacings yields a relative contribution of approximately 0.25 (i.e. 25%) to the secondary magnetic field at the receiver coil.

Suppose now that our homogeneous halfspace has a conductivity of 20 millimhos per meter (50 ohmmeters). The equipment having been calibrated according to equation (2), the output meter indicates 20 millimhos per meter. From Figure 7 we observed that the material below two intercoil spacings contributed 25% to the secondary magnetic field and therefore 25% to the indicated meter reading. Suppose that we replace this deep material with an infinitely resistive (zero conductivity) substance. Since we have reduced to zero the 25% that this material contributed to the meter reading the new reading will be 75% of 20, or 15 millimhos per meter. Conversely, if we leave all of the material below two intercoil spacings at 20

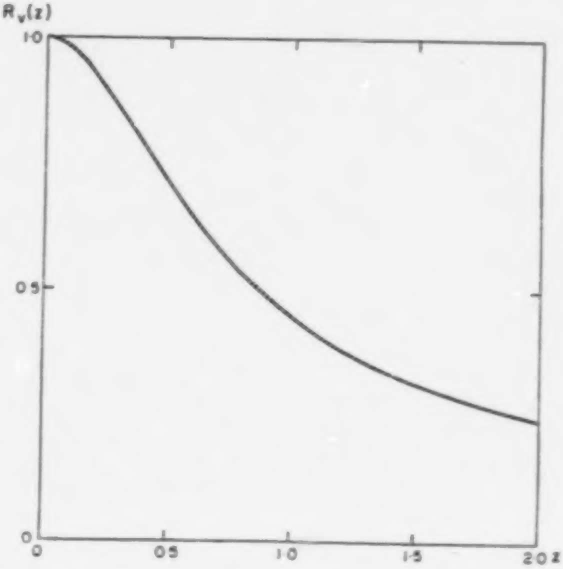


FIGURE 7. Cumulative response versus depth for vertical dipoles. $R_V(z)$ is the relative contribution to H_s from all material below a (normalized) depth z.

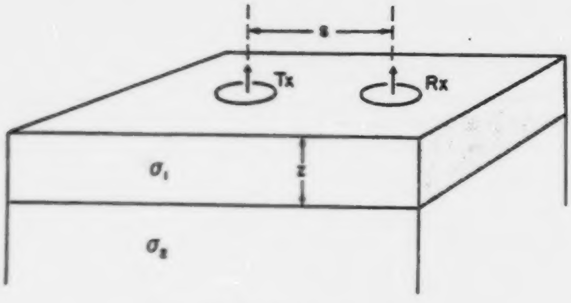


FIGURE 8. Two layer earth model.

millimhos per meter but make all material above two intercoil spacings infinitely resistive the meter reading will fall from the original 20 millimhos per meter for the homogeneous half space to 5 millimhos per meter, since, if all of the material below two intercoil spacings contributed 25% of the meter reading, all of the material above two intercoil spacings must contribute 75%; when removed the meter reading becomes 0.25 × 20 or 5 millimhos per meter.

From this example we see that there is a simple way to calculate the instrument reading on an arbitrarily layered earth as long as the intercoil spacing is much less than the skin depth in all of the layers. We simply add the contribution from each layer independently, weighted according to its conductivity and depth according to Figure 7. For example assume that we have a two-layer case as shown in Figure 8. The contribution from the upper layer is given by

$$\sigma_a = \sigma_1[1 - R_V(z)] \qquad (4a)$$

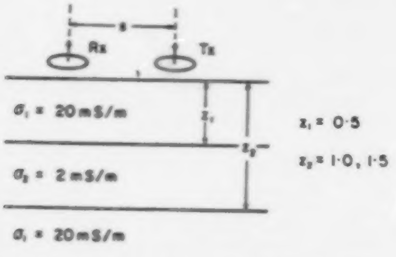
since all of the material below zero depth yields a relative contribution of unity or 100% to the meter reading. Conversely all of the material in the lower layer adds a contribution given by

$$\sigma_a = \sigma_2 R_V(z) \qquad (4b)$$

and the actual instrument reading will therefore be the sum of these two quantities

$$\sigma_a = \sigma_1[1 - R_V(z)] + \sigma_2 R_V(z) \qquad (5)$$

If the earth is three-layered as shown in Figure 9 the same procedure is employed to determine the instrumental response. In this example the calculations are performed for different middle layer thicknesses.



$$\sigma_a = \sigma_1[1-R(z_1)] + \sigma_2[R(z_1)-R(z_2)] + \sigma_3 R(z_2)$$

$$z_2 = 1{\cdot}0,\ \sigma_a = 20[1-0{\cdot}70] + 2[0{\cdot}70-0{\cdot}44] + 20\times 0{\cdot}44 = 15{\cdot}3 \text{ mmho/m}$$

$$z_2 = 1{\cdot}5,\ \sigma_a = 20[1-0{\cdot}70] + 2[0{\cdot}70-0{\cdot}32] + 20\times 0{\cdot}32 = 13{\cdot}2 \text{ mmho/m}$$

FIGURE 9. Calculation of response to three layer earth – center layer thickness varying.

The ease with which such calculations are performed facilitates survey preparation and interpretation. It is sometimes possible to make advance estimates of the electrical properties of the materials to be encountered during a survey or, alternatively, once on-site the operator can obtain the same information from sample measurements of the different materials. The procedures outlined above are then employed to estimate the apparent conductivity measured under various terrain conditions. Examples of such calculations for the EM31 are shown in Figure 10. As is seen in the appendix the algebraic expressions for $\phi(z)$ and R(z) are very simple and are easily programmed on hand held calculators.

In Figure 10 the vertical dimensions are greatly exaggerated with respect to the horizontal dimensions. The question arises as to what degree of lateral uniformity is required before the earth can be considered as horizontally stratified or homogeneous. Survey experience indicates that if the ground conductivity does not significantly vary with horizontal distance within a radius of one intercoil spacing from the instrument the ground can be considered to be laterally uniform.

The above discussion referred to the use of vertical transmitter/receiver dipoles; it is equally possible to construct a cumulative response function for the horizontal coplanar dipole configuration and Figure 11 illustrates this function for both coil configurations. A comparison of the two curves illustrates that the vertical dipole mode of operation has approximately twice the effective exploration depth of the horizontal dipole mode.

IV. 3. Comparison with Conventional Resistivity Techniques

Many readers will be familiar with the two-layer curves employed to interpret data from conventional resistivity surveys using a Wenner array of four equally spaced electrodes. Using the techniqnes described in the previous section it is a simple matter to calculate two-layer curves for the electromagnetic technique; Figure 12 shows such curves for both the vertical and horizontal dipole configurations superimposed on standard Wenner curves. The general shape is similar but there are marked differences in detail. For vertical coplanar transmitter/receiver dipoles we see that when the substrate is the more resistive the response of the two systems is similar; however when the substrate is the more conductive the electromagnetic technique sees deeper in that the influence of the substrate, for a given conductivity contrast, is felt at smaller intercoil spacing than inter-electrode spacing. This is a general characteristic of electromagnetic systems which prefer to look through an insulator to a conductor rather than through a conductor to an insulator.

For the horizontal dipole configuration if the lower layer is the more resistive the effective exploration depth of the inductive technique is slightly less than the Wenner array; however, once again, in the case where the lower layer is the more conductive the exploration depth of the inductive technique is substantially greater.

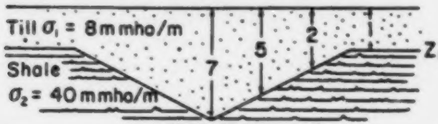
IV. 4. Resolution of Two-Layered Earth by Varying Intercoil Spacing

The principal advantage of the inductive electromagnetic technique over conventional resistivity lies in the speed and accuracy with which lateral changes of terrain conductivity can be measured. However this technique can also be used to measure the vertical variation of conductivity by expanding the intercoil spacing in a manner analogous to that in which the electrode spacing is expanded in conventional resistivity sounding techniques. The current state-of-the-art, however, is such that relatively few intercoil spacings can be employed; for example the EM34-3 can be operated with an intercoil spacing of 10, 20 or 40 meters. This feature is somewhat mitigated by the fact that the instruments can be used in either the vertical or horizontal dipole modes which, as shown in a previous section, exhibit different sensitivity to various depths thus yielding more information than would be available by simply using three spacings with one coil orientation.

To interpret a two-layef geometry the two-layer curves for both dipole configurations are superimposed on a common plot as shown

CROSS-SECTIONS

BURIED RIVER VALLEY

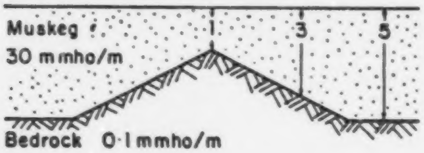

Till σ_1 = 8m mho/m
Shale
σ_2 = 40 mmho/m
7
5
2
1
Z_1

$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{40}{8} = 5$$

Z_1 (m)	σ_a (mmho/m)
1	32·6
2	26·9
5	18·6
7	16·0

BEDROCK HIGH

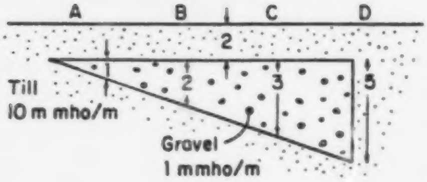

Muskeg
30 m mho/m
1
3
5
Bedrock 0·1 mmho/m

$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{0{\cdot}1}{30} = 0{\cdot}0033$$

Z_1(m)	σ_a (m mho/m)
1	6·9
3	15·9
5	20·1

GRAVEL DEPOSIT


A
B
C
D
2
2
3
5
Till
10 m mho/m
Gravel
1 mmho/m

$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2[R(Z_1) - R(Z_2)] + k_3 R(Z_2)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{1}{10} = 0{\cdot}10$$

$$k_3 = \frac{\sigma_3}{\sigma_1} = 1{\cdot}00$$

station	σ_a (m mho/m)
A	8·9
B	8·2
C	7·7
D	6·9

FIGURE 10. FM31 calculated response across various geological features, using R (Z) corrected for instrument operation at waist (1 meter) height. Coil separation s = 3.67 meters.

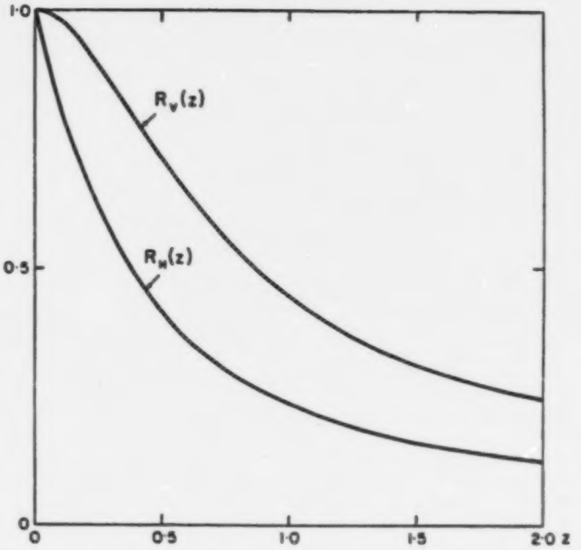


FIGURE 11. Cumulative response versus depth for vertical and horizontal dipoles.

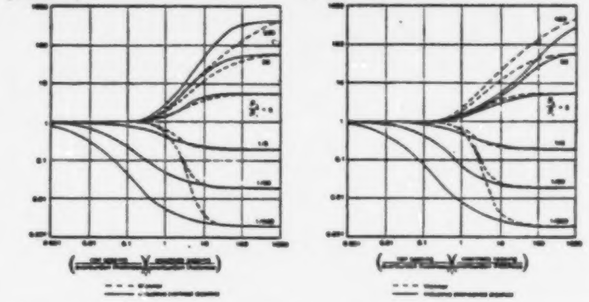


FIGURE 12. Comparison of Wenner array and inductive electromagnetic sounding curves for a two layer earth.

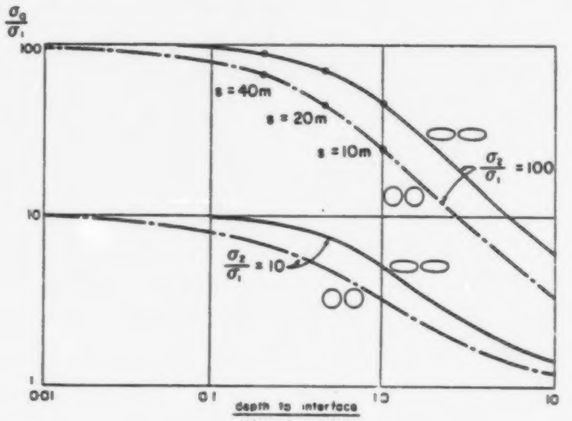


FIGURE 13. Two layer earth response curves (σ_2/σ_1 = 10,100; intercoil spacing varied). Dots indicate typical survey results.

in Figure 13. The six data points obtained by making measurements with two coil orientations and three intercoil spacings are plotted to the same scale on a piece of transparent paper and are translated vertically and horizontally on the two-layer curves to ascertain whether a satisfactory fit can be achieved. In the event that such a fit can be made, the earth does exhibit two-layer characteristics and the values of conductivity for both layers and the thickness of the upper layer are directly read off.

IV. 5. Resolution of Two-Layered Earth by Varying Instrument Height

In the case of the EM31 the intercoil spacing is rigidly fixed so that the technique described above is not available to analyse a layered earth. It is, however, possible to raise the instrument above the ground, measuring the apparent conductivity as a function of instrument height for both the vertical and horizontal dipole configurations. This has the effect of shifting the response curves of Figure 6 upwards through the various regions of the earth and the variation of apparent conductivity with height is therefore of diagnostic value in determining the nature of any layering. It is a straightforward matter to calculate the response of the instrument as a function of height for various two-layered earth geometries and typical curves are shown in Figure 14b. To use the curves one simply plots the measured apparent conductivity versus height for both coil configurations on a piece of transparent paper to the same scale as Figure 14b and shifts the plotted data vertically until good agreement is achieved with one of the curves, whereupon the two conductivities and the upper layer thickness are immediately determined as in the illustrated case history of Figure 14c.

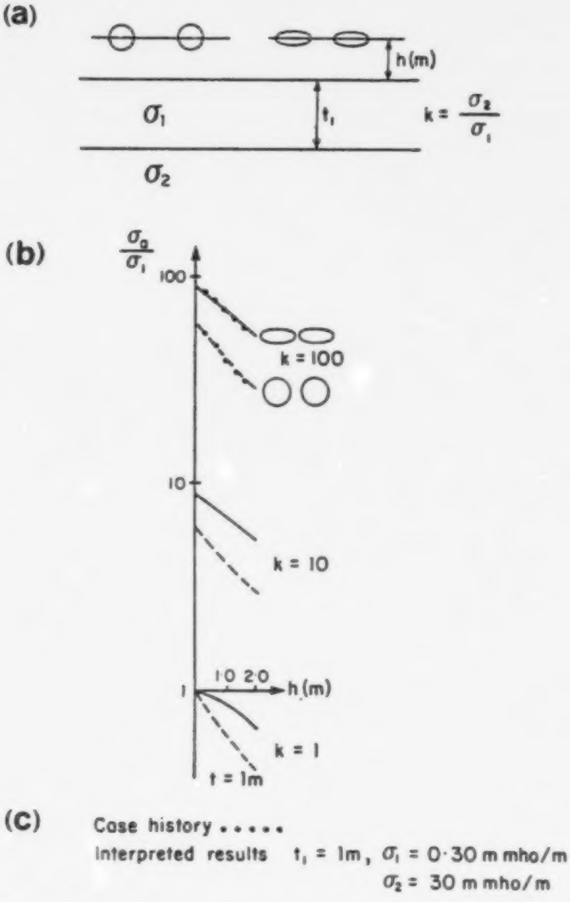


FIGURE 14. Two layer earth response curves (σ_2/σ_1 = 1, 10, 100; instrument height varied). Dots are actual survey results.

In the event that the conductivity of either one of the two layers is known to be much less than the other, so that its contribution to the meter reading is negligible, it is simply necessary to lay the instrument on the ground, take a reading, lay it on its side, take a second reading, and from these two values one can immediately calculate the conductivity of the more conductive layer and the thickness of the upper layer.

V. ADVANTAGES AND DISADVANTAGES OF INDUCTIVE TERRAIN CONDUCTIVITY MEASUREMENTS

V. 1. Advantages

The advantages of the use of inductive electromagnetic techniques to measure terrain conductivity are as follows:

(i) *Excellent resolution in conductivity.* It was stated in Section I that a problem with conventional resistivity was that the presence of localized resistivity inhomogeneities near the potential electrodes caused large errors. If we examine the current flow in a homogeneous halfspace for the inductive technique described herein we realize that in the vicinity of the transmitter the current density is very high and we might expect the presence of a conductive inhomogeneity located here to have a large effect. However where the current density is high, the radius of the current loops is small and their distance from the receiver coil large, so that these loops do not couple well magnetically with the receiver. The effect of changing this current by varying the local conductivity is consequently negligible. The lateral extent of the volume of earth whose conductivity is sensed by the inductive technique is approximately the same as the vertical depth. The result is that small changes in conductivity, for example of the order of 5% or 10%, are easily and accurately measured.

(ii) *No current injection problems.* Since currents are magnetically induced in the earth, current injection problems encountered with conventional resistivity in materials such as gravel, bedrock, permafrost, snow and ice, etc., are not encountered with this type of instrumentation.

(iii) *Simple multi-layered earth calculations.* This matter is dealt with at length in Section IV.

(iv) *Easy, rapid measurements.* A problem with the conventional Wenner array is that in order to survey to an effective depth a the array must be 3a in length and the total length of wire required 4a, used in four sections. This presents many opportunities for snagging and breaking the wire. Furthermore each measurement requires insertion of four electrodes and relatively careful measurement of the inter-electrode spacing. These features are avoided with the inductive electromagnetic techniques and it is no exaggeration to say that a survey can often be carried out five to ten times faster using this technique. Indeed with either the EM31 or the EM34-3 it is usually possible under average terrain conditions to survey 5 to 7 line-kilometers a day with a station spacing of 25 or 50 meters.

V. 2. Disadvantages

As with all geophysical instruments, there are some limitations and disadvantages to the use of inductive electromagnetic techniques and these are as follows:

(i) *Limited dynamic range (1 – 1000 mmhos per meter).* At low values of terrain conductivity it becomes difficult to magnetically induce sufficient current in the ground to produce a detectable magnetic field at the receiver coil. Conversely at high values of conductivity the quadrature component of the received magnetic field is no longer linearly proportional to terrain conductivity as is shown in the appendix.

(ii) *Setting and maintaining the instrument zero.* Ideally in order to set the zero the instrument would be suspended in free space and the zero set there. The more acceptable alternative is to search out a region of very resistive ground, to accurately measure its conductivity using conventional techniques, and to set the instrumental zero at that location. This is the procedure which is actually followed.

It is necessary that this zero be accurately maintained over long periods of time and over the wide variations of temperature encountered during geophysical survey in various parts of the world. This produces tight constraints on the circuitry, with the result that the zero may be in error by up to ±0.2 mmhos per meter. Such an error would be negligible over the usual range of terrain conductivities; however in the event that measurements are being made on highly resistive ground the zero error can become significant.

(iii) *Limited Vertical Sounding Capability*. In theory it is possible to use a system such as the EM34-3 at a continuum of intercoil spacings to yield more information about electrical layering in the ground. To achieve a wide variety of inter-electrode spacings with conventional resistivity equipment is simple; in the case of the inductive electromagnetic technique the rapid fall-off of the magnetic field from the dipole transmitter introduces a serious dynamic range problem. In due course there will undoubtedly be instrumentation with a wider variety of spacings at the expense of additional complexity.

VI. CASE HISTORIES

This section describes several case histories obtained with the EM31 and the EM34. The surveys (i) illustrate the resolution in conductivity that can be achieved, (ii) compare the results obtained with conventional resistivity and (iii) illustrate the use of the latter for locating sand, gravel and conductive minerals, determining bedrock topography (including locating a buried river channel) and mapping the pollution plume from a land-fill site. In some cases the indicated conductivity has been converted to resistivity to facilitate comparison with conventional resistivity survey results.

Case History #1

Location:	Mississauga, Ontario
Instrument:	EM31
Application:	Illustrates resolution and repeatability of EM31

For this case history a Rustrak chart recorder was used to monitor the output of an EM31. A line of length 200 meters was traversed in a field in both easterly and westerly directions. Figure 15 demonstrates that the instrument is resolving conductivity changes of less than 1 mmho/m (1% of full scale deflection) and that the repeatability is of the same order. In fact the repeatability is limited in this case by the resolving power of the chart recorder itself. It should furthermore be noted that the instrument is detecting spatial changes in conductivity of a few meters in length – compatible with the intercoil spacing of 3.7 meters.

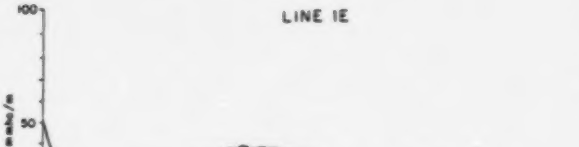


FIGURE 15.

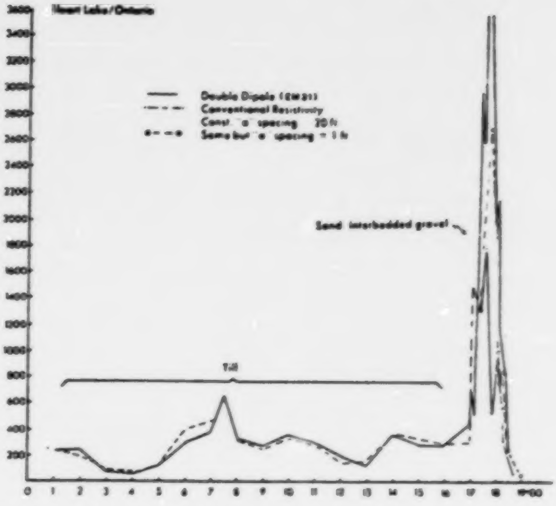


FIGURE 16. Test survey line – Heart Lake, Ont.

Case History #2

Location:	Hearth Lake, Ontario
Instruments:	EM31 Conventional resistivity apparatus
Application:	Location of sand/gravel Comparison of EM31 and conventional resistivity

In this survey a line 1900 ft. (580 meters) in length was surveyed with a measurement interval of 100 ft. (30 meters). The survey area was generally located on a buried esker, however the last few survey stations, 17 + 00 to 19 + 00, traversed a region of exposed sand and gravel (often occurring in the form of concretions) and over this portion of the line measurements were made every 10 ft. (3.0 meters).

The conventional resistivity profile was carried out using a Wenner array with an a spacing of 20 ft. (6.1 meters) except between stations 17 + 00 and 19 + 00 where the a spacing was reduced to 1 ft. (0.30 meters).

In general the correlation between the two sets of data is excellent, and demonstrates the ability of the EM31 to generate good quantitative data even in regions of low conductivity. Over the esker the EM31 was actually read continuously down the line – the data was recorded only at the 100 ft. intervals, with the exception of the reading at station 7 + 50 which was also recorded since it was noted that a conductivity low occurred there. Such an anomaly was, of course, missed by the conventional resistivity where measurements were only made every 100 ft.

Both sets of data become rather erratic between stations 17 + 00 and 19 + 00 as a result of the very rapid lateral changes in resistivity arising from the concreted material referred to above.

Case History #3

Location:	Cavendish, Ontario.
Instrument:	EM31
Application:	Location of metallic type conductors

This survey line, of length 2000 ft. (610 meters), is located at a site

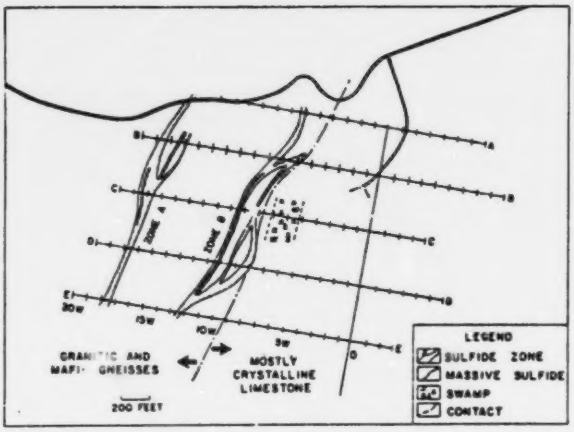


FIGURE 17. Geologic map of the Cavendish test site and the grid of traverse lines used in geophysical studies (after Ward et al [3]).

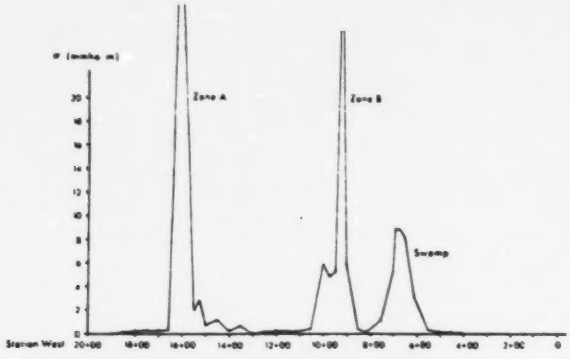


FIGURE 18. EM31 survey of Cavendish test range Line 'C'.

in Ontario which is often used by Canadian instrumentation manufacturers to test new electromagnetic geophysical equipment. The survey, along line C, illustrates response from both the swamp and the two zones of metallic mineralization. Although measurements were only taken every 50 ft. (15 meters) both zones are well delineated and when such high responses are encountered localization to within a few meters is quickly and easily carried out.

Inasmuch as the EM31 and EM34-3 were designed to map terrain conductivity at the conductivity levels encountered in typical soils both instruments are extremely sensitive electromagnetic detectors. For example on the most sensitive scale, full scale deflection for the EM31 is 800 ppm of the primary magnetic field and for the EM34-3 it is 3800 ppm. Such sensitivity makes either instrument useful for detecting metallic type conductors at what are very low conductivity levels by normal standards.

Case History #4

Location:	Mississauga, Ontario
Instruments:	EM31, EM34
Application:	Determination of bedrock topography

Total line length for this survey was 8400 ft. (2600 meters) and measurements were made every 100 ft. (30 meters) with both the EM31 and the EM34 – an earlier version of the EM34-3 which had two intercoil spacings vis. 100 ft. (30 meters) and 50 ft. (15 meters). The survey was performed to outline the cross-sectional profile of a

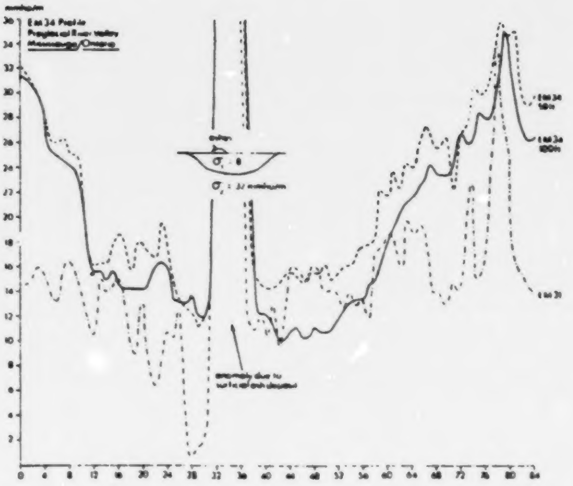


FIGURE 19. EM31 and EM34 survey line over preglacial river valley, Mississauga, Ontario.

buried preglacial river valley whose existence had been suggested from water-well data. At either intercoil spacing the time required for the EM34 profile was 1-1/2 hours, resulting in approximately one survey measurement per minute – including the time to walk the 100 feet between measurement stations. The time taken for the subsequent EM31 survey was similar.

Typical bedrock conductivity in the area is approximately 30 mmho/m, whereas an average value for the conductivity of the infilling glacial till is of the order of 8 to 12 mmho/m. Thus the EM34 at either intercoil spacing yields approximately 30 mmho/m at the valley edges where the overburden is thin and 12 to 14 mmho/m at the valley centre. The EM31 yields values of 14 to 18 mmho/m at the valley edges (slightly affected by the presence of bedrock) and approximately 10 mmho/m at the valley centre. The interpreted depth of the valley, based on the model shown in the figure, is approximately 120 feet (36 meters) which is in reasonable agreement with the water-well data value of 150 feet (45 meters), bearing in mind that the three sets of data show that a two-layer model is an over simplification.

The conductivity high which occurs between stations 32 and 38 results from a very large pile of waste furnace ash lying on the surface.

Case History #5

Location:	Camp Borden, Ontario
Instruments:	EM31, EM34 Conventional resistivity apparatus
Application:	Mapping groundwater salinity Comparison of EM34 and conventional resistivity

Geophysical surveys were carried out over a sanitary landfill site using, in addition to other instruments, an EM31, EM34 and conventional resistivity [4]. The survey results in the accompanying figures illustrate the good agreement between these techniques and also indicate the reduction in survey time achieved using inductive electromagnetic techniques. Particularly interesting are the vertical variations in resistivity as shown by the EM31 at 3.7 m intercoil spacing and the EM34 at 15 and 30 m spacing.

VII. SUMMARY

This technical note describes in detail the principles of mapping the electrical conductivity of the ground using magnetically induced

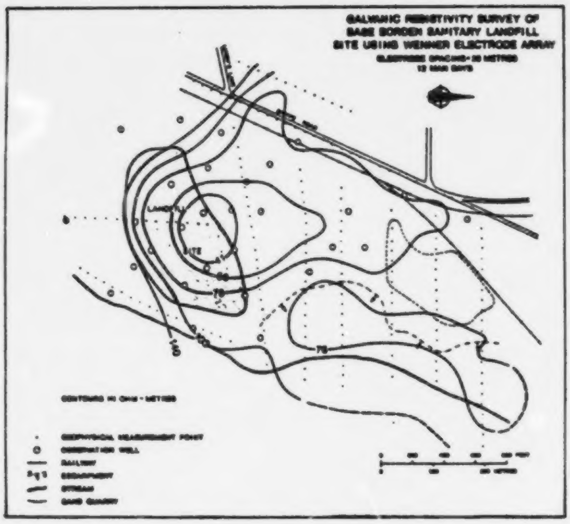

GALVANIC RESISTIVITY SURVEY OF
BASE BORDEN SANITARY LANDFILL
SITE USING WENNER ELECTRODE ARRAY
LANDFILL
CONTOURS IN OHM-METRES
GEOPHYSICAL MEASUREMENT POINT
OBSERVATION WELL
RAILWAY
ESCARPMENT
STREAM
SAND QUARRY

FIGURE 20(a).

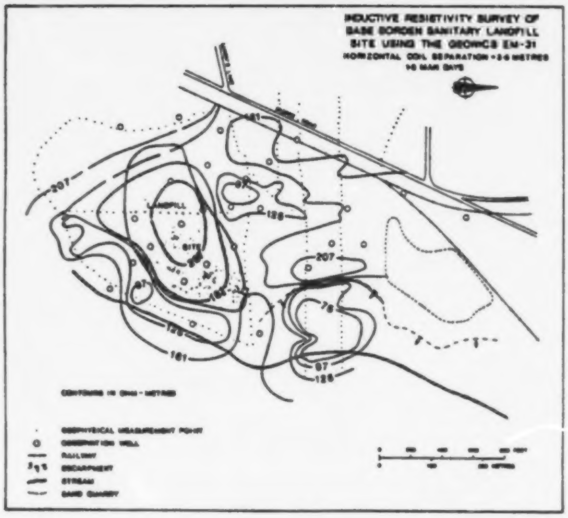

INDUCTIVE RESISTIVITY SURVEY OF
BASE BORDEN SANITARY LANDFILL
SITE USING THE GEONICS EM-31
LANDFILL
SITE
207
128
161
97
79
CONTOURS IN OHM-METRES
GEOPHYSICAL MEASUREMENT POINT
OBSERVATION WELL
RAILWAY
ESCARPMENT
STREAM
SAND QUARRY

FIGURE 20(b).

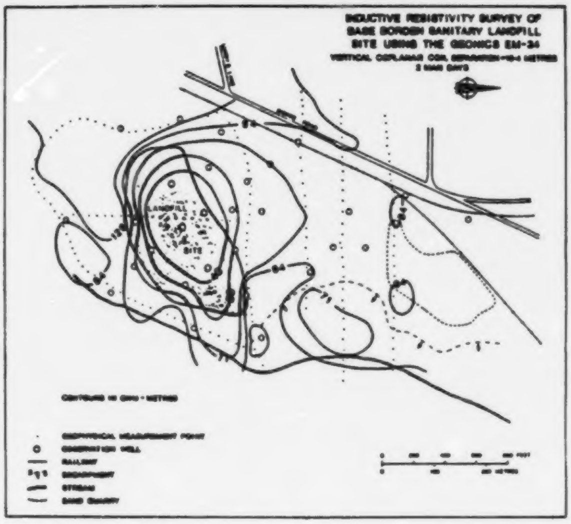

INDUCTIVE RESISTIVITY SURVEY OF
BASE BORDEN SANITARY LANDFILL
SITE USING THE GEONICS EM-34
LANDFILL
SITE
CONTOURS IN OHM-METRES
GEOPHYSICAL MEASUREMENT POINT
OBSERVATION WELL
RAILWAY
ESCARPMENT
STREAM
SAND QUARRY

FIGURE 20(c).

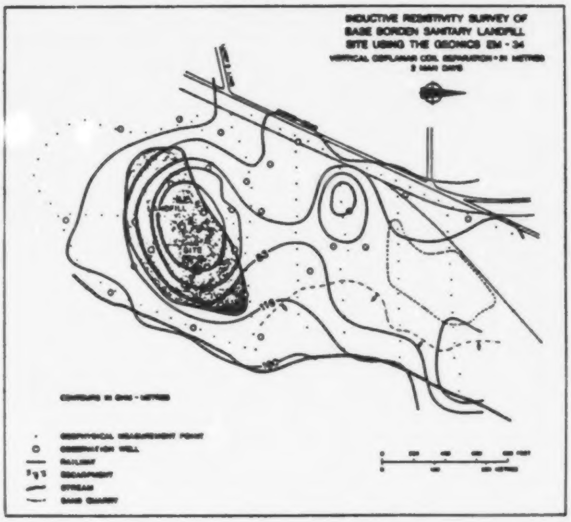

INDUCTIVE RESISTIVITY SURVEY OF
BASE BORDEN SANITARY LANDFILL
SITE USING THE GEONICS EM-34
LANDFILL
SITE
CONTOURS IN OHM-METRES
GEOPHYSICAL MEASUREMENT POINT
OBSERVATION WELL
RAILWAY
ESCARPMENT
STREAM
SAND QUARRY

FIGURE 20(d).

currents at low frequencies. It has been shown that certain advantages can be derived from working at low values of induction number. Amongst these are excellent resolution in conductivity, a substantial reduction in man-hours necessary to carry out a conductivity survey and a simplification in the calculation of layered earth response.

Two points should be kept constantly in mind when performing surveys of this type to map geology. The first is that these instruments map only the electrical conductivity. If the conductivity does not vary significantly with the geological environment, or if parameters other than the geology also influence the conductivity, the survey results may be difficult to interpret.

The second point is that measurement of terrain conductivity, like any other geophysical measurement, must begin and end with geology. Such measurements are only an aid to help visualize geological conditions which cannot be seen. It is always necessary to interpret geophysical data against known geology from out-crops, boreholes, or any other such "bench marks". Geophysical measurements can be very effective by allowing interpolation between such sources, or extrapolation away from them. However in every case knowledge derived from geophysical measurements must be eventually reconfirmed against known geological conditions.

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(1) Keller, G.V., Frischknecht, F.C. Electrical Methods in Geophysical Prospecting. Pergamon Press 1966.

(2) Wait, J.R. 1962. A Note on the Electromagnetic Response of a Stratified Earth. Geophysics V.27, pp 382-85.

(3) Ward, S.H.; Pridmore, D.F.; Rijol, Glenn W.E. Multispectral Electromagnetic Exploration for Sulphides. Geophysics Vol. 39 No. 5 p. 666. 1974.

(4) Survey carried out by Dr. J. Greenhouse, University of Waterloo, Waterloo, Ontario.

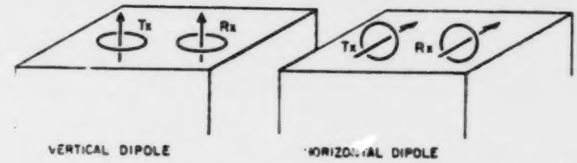


FIGURE AI. Vertical and horizontal dipole coil configurations.

APPENDIX: Theory of Operation at Low Induction Numbers

Consider the two coil configurations shown in Figure AI. In each case the transmitter coil is energized with alternating current at a frequency f Hertz. The measured quantity is the ratio of the secondary magnetic field H_s at the receiver when both coils are lying on the surface of the homogeneous half-space of conductivity σ to the primary magnetic field H_p in the absence of the half-space (i.e. as if the coils were in free space). The spacing between the coils is s meters.

The field ratios for vertical and horizontal dipole configurations are given by equations (1) and (2) respectively.

$$\left(\frac{H_s}{H_p}\right)_V = \frac{2}{(\gamma s)^2}\{9 - [9 + 9\gamma s + 4(\gamma s)^2 + (\gamma s)^3]\,e^{-\gamma s}\} \quad (1)$$

$$\left(\frac{H_s}{H_p}\right)_H = 2\left[1 - \frac{3}{(\gamma s)^2} + [3 + 3\gamma s + (\gamma s)^2]\frac{e^{-\gamma s}}{(\gamma s)^2}\right] \quad (2)$$

where $\gamma = \sqrt{i\omega\mu_o\sigma}$

$\omega = 2\pi f$

f = frequency (Hz)

μ_o = permeability of free space

$i = \sqrt{-1}$.

These expressions are complicated functions of the variable γs which is in turn a reasonably complicated (complex) function of frequency and conductivity. However, as will be shown below, under certain conditions they can be greatly simplified.

A well known characteristic of a homogeneous half-space is the electrical skin depth δ, which is defined as the distance in the half-space that a propagating plane wave has travelled when its amplitude has been attenuated to 1/e of the amplitude at the surface. The skin depth is given by

$$\delta = \sqrt{\frac{2}{\omega\mu_o\sigma}} = \frac{\sqrt{2i}}{\gamma} \quad (3)$$

and therefore

$$\gamma s = \sqrt{2i}\,\frac{s}{\delta} \quad (4)$$

The ratio s/δ, the intercoil spacing divided by the skin depth, is defined as the induction number B, whereupon

$$\gamma s = \sqrt{2i}\,B \quad (5)$$

Now if B is much less than unity (ie $\gamma s \ll 1$) it is a simple matter to show that the field ratios of equations (1) and (2) reduce to the simple expression

$$\left(\frac{H_s}{H_p}\right)_V \simeq \left(\frac{H_s}{H_p}\right)_H \simeq \frac{iB^2}{2} = \frac{i\omega\mu_o\sigma s^2}{4} \quad (6)$$

which is the equation given in Section II.

The magnitude of the secondary magnetic field is now directly proportional to the ground conductivity and the phase of the secondary magnetic field leads the primary magnetic field by 90°.

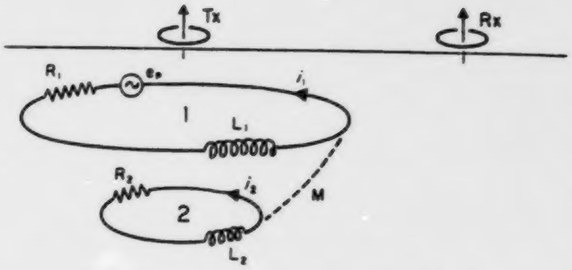


FIGURE AII. Electrical model for vertical dipoles.

To make B much less than unity we see that we must make s very much less than δ and thus

$$\omega \ll \frac{2}{\mu_o\sigma s^2} \quad (7)$$

That is, having decided on a value for s (which fixes the effective depth of penetration under the condition $B \ll 1$), the maximum probable ground conductivity is estimated and the operating frequency is chosen so that equation (7) is always satisfied.

The apparent conductivity which the instrument reads is then defined by

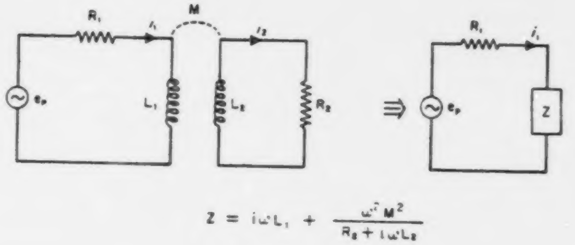
$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right)_{\substack{\text{quadrature}\\ \text{component}}} \quad (8)$$

To examine the reasons for this simplification let us focus our attention on the vertical dipole coil configuration shown in Figure AII since symmetry makes this configuration the simplest to understand.

Consider current loop 1. The primary emf e_p causing this current to flow is given (through Faraday's law) by the time rate of change of the primary magnetic flux from the transmitter through this loop. Three impedances cause the current to be limited. These arise from (i) the electrical resistance R_1 of the loop, (ii) the fact that the current i_1 generates its own magnetic field which causes a time-varying secondary magnetic flux through the loop (self-inductance, L_1), and (iii) the fact that all other current loops such as i_2 generate their own magnetic fields which in turn cause a time-varying magnetic flux to link with loop 1 (mutual-inductance, M).

The equivalent circuit for this configuration is easily derived from elementary circuit theory with the result shown in Figure AIII.

The complex impedance Z incorporates all of the affects of magnetic coupling between current loop 1 and any other current loop 2. We see from this expression that Z can be made arbitrarily small by reducing $\omega = 2\pi f$, the operating frequency. When Z is thus



$$Z = i\omega L_1 + \frac{\omega^2 M^2}{R_2 + i\omega L_2}$$

$$i_1 = \frac{e_p}{R_1 + Z}$$

FIGURE AIII. Equivalent circuit for model of Figure AII.

made much smaller than R_1 the current flow in loop 1 is simply given by

$$i_1 = \frac{e_p}{R_1} = \frac{i\omega\phi_p}{R_1} = i\omega\phi_p G_1 \qquad (9)$$

where ϕ_p = primary flux linking loop 1
G_1 = conductance of loop $1 (G_1 = 1/R_1)$
$i = \sqrt{-1}$

We see that the magnitude of the current is linearly proportional to the loop conductance and furthermore that the phase of the current leads the primary flux by 90°. Since the secondary magnetic field at the receiver from current i_1 is in phase with and directly proportional to i_1 it too will be directly proportional to G and will lead the primary flux by 90°. Thus

$$\left(\frac{H_s}{H_p}\right) \propto i\omega G_1 \qquad (10)$$

which has the same dependence on frequency and conductance as equation (6). We infer therefore, that the condition $B \ll 1$ is equivalent to stating that for all current loops that affect the receiver output the operating frequency is so low that we can ignore any magnetic coupling between the loops. Thus the current that flows in any loop is (i) completely independent of the current that flows in any other loop since they are not magnetically coupled and (ii) is only a function of the primary magnetic flux linking that loop and of the local ground conductivity.

The lack of interaction between current loops is of great importance in simplifying the data reduction procedures. Of equally great significance is the fact that for any value of B and for any orientation of a magnetic dipole (or indeed of any magnetic source) over either a uniform halfspace or a horizontally stratified earth it can be shown that all current flow is horizontal. That this is the case for a vertical dipole is easy to see from symmetry; for a horizontal dipole it is less evident but equally true. Thus, in a horizontally layered earth no current crosses an interface which is fortunate since, if it did, changing either of the conductivities would, by virtue of refraction of the current, change the direction of the current as it flowed from one medium to the other.

If no current flow crosses an interface and if there is no magnetic coupling between current loops, changing the conductivity of any one of the layers of a horizontally stratified earth will not alter the geometry of the current flow. Varying the conductivity of any layer will proportionately vary only the magnitude of the current in that layer. To calculate the resultant magnetic field at the surface of a horizontally layered earth it is simply necessary to calculate the independent contribution from each layer, which is a function of its depth and conductivity, and to sum all the contributions.

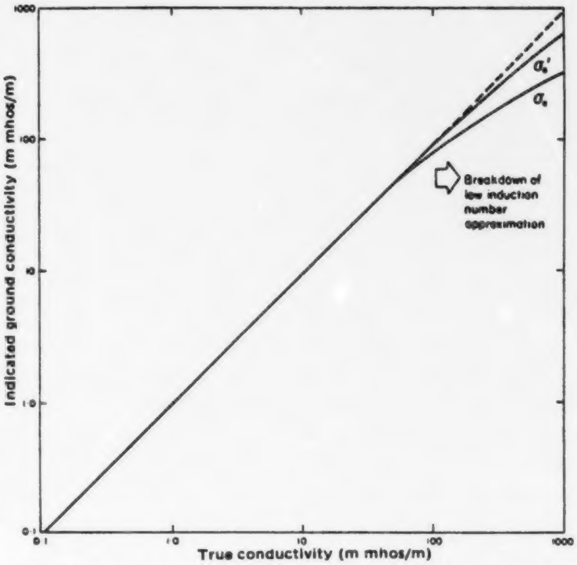


FIGURE AIV. Plot of indicated conductivity for EM31 versus true (homogeneous half-space) conductivity for both vertical (σ_a) and horizontal (σ_a') dipoles.

The functions $\phi(z)$ and $R(z)$ discussed in Section II define the relative influence of current flow as a function of depth. Their derivation is involved and will not be given here. The resultant expressions are, however, simple and easily programmed into hand calculators:

$$\phi_V(z) = \frac{4z}{(4z^2 + 1)^{3/2}} \qquad (11)$$

$$\phi_H(z) = 2 - \frac{4z}{(4z^2 + 1)^{1/2}} \qquad (12)$$

$$R_V(z) = \frac{1}{(4z^2 + 1)^{1/2}} \qquad (13)$$

$$R_H(z) = (4z^2 + 1)^{1/2} - 2z \qquad (14)$$

where z is the depth divided by the intercoil spacing.

Finally it should be noted that for a given frequency and intercoil spacing as the terrain conductivity increases the approximation of equation (6) eventually breaks down and the instrumental output is no longer proportional to terrain conductivity. This effect is illustrated in Figure AIV. which plots apparent (indicated) conductivity against true (homogeneous halfspace) conductivity for both vertical and horizontal transmitter/receiver dipoles for the operating parameters of the EM31. As would be expected the horizontal dipoles exhibit linearity to greater values of conductivity as a result of the reduced depth of penetration in this configuration.

APPENDIX C

MTC TEST HOLE AND SAMPLE ANALYSIS DATA

Notes:

1. See Dwg. No. 1 for locations of test holes.
2. See Appendix F for explanation of soil description abbreviations.
3. "Unsuitable"
   Analysis" means that the material is not acceptable for any aggregate use.
4. "Acceptable"AND "Borderline Acceptable" in the column headed "Results of Lab Analysis" means
   that the material is acceptable or borderline acceptable for use for select subgrade material.
5. Details of the sample analysis data are presented following the test hole data.

Test Hole No.	Strata Depth (metres)	Soil Description	Laboratory Sample No.	Results of Lab Analysis
T.H. No.1	0 - 0.2	Tps		
	0.2 - 3.0	Br VF Si Sa		
	3.0 - 9.5	Gry Si Cl - wet, firm @8.0 m		
T.H. No.2	0 - 0.2	Tps		
	0.2 - 2.0	Br Si VF Sa		
	2.0 - 8.0	Br Si Cl - wet		
	8.0 - 9.5	Br Cl Till - firm		
T.H. No.3	0 - 0.2	Tps		
	0.2 - 8.2	Br Si Cl - W.T. @ 6.3m		
	8.2 - 9.5	Br Si Cl Till - firm		
T.H. No.4	0 - 0.2	Tps		
	0.2 - 4.0	Br Sa Si - wet	85A0 2020	unsuitable
	4.0 - 8.0	Gry Cl Si - wet	85A0 2021	unsuitable
	8.0 - 9.5	Gry Si Cl Till - firm	85A0 2022	unsuitable
T.H. No.5	0 - 0.2	Tps		
	0.2 - 8.0	Br Si Cl - wet		
	8.0 - 9.5	Gr Si Cl - firm		
T.H. No.6	0 - 0.2	Tps		
	0.2 - 5.0	Br F Sa - wet @ 3.0 m	85A0 2024	borderline acceptable
	5.0 - 6.0	Br Si Cl		
	6.0 - 9.0	Br Si Sa with Si Cl layers - wet		
	9.0 -12.5	Gry Si Cl - firm		
	12.5 +	Si Cl Till - firm		

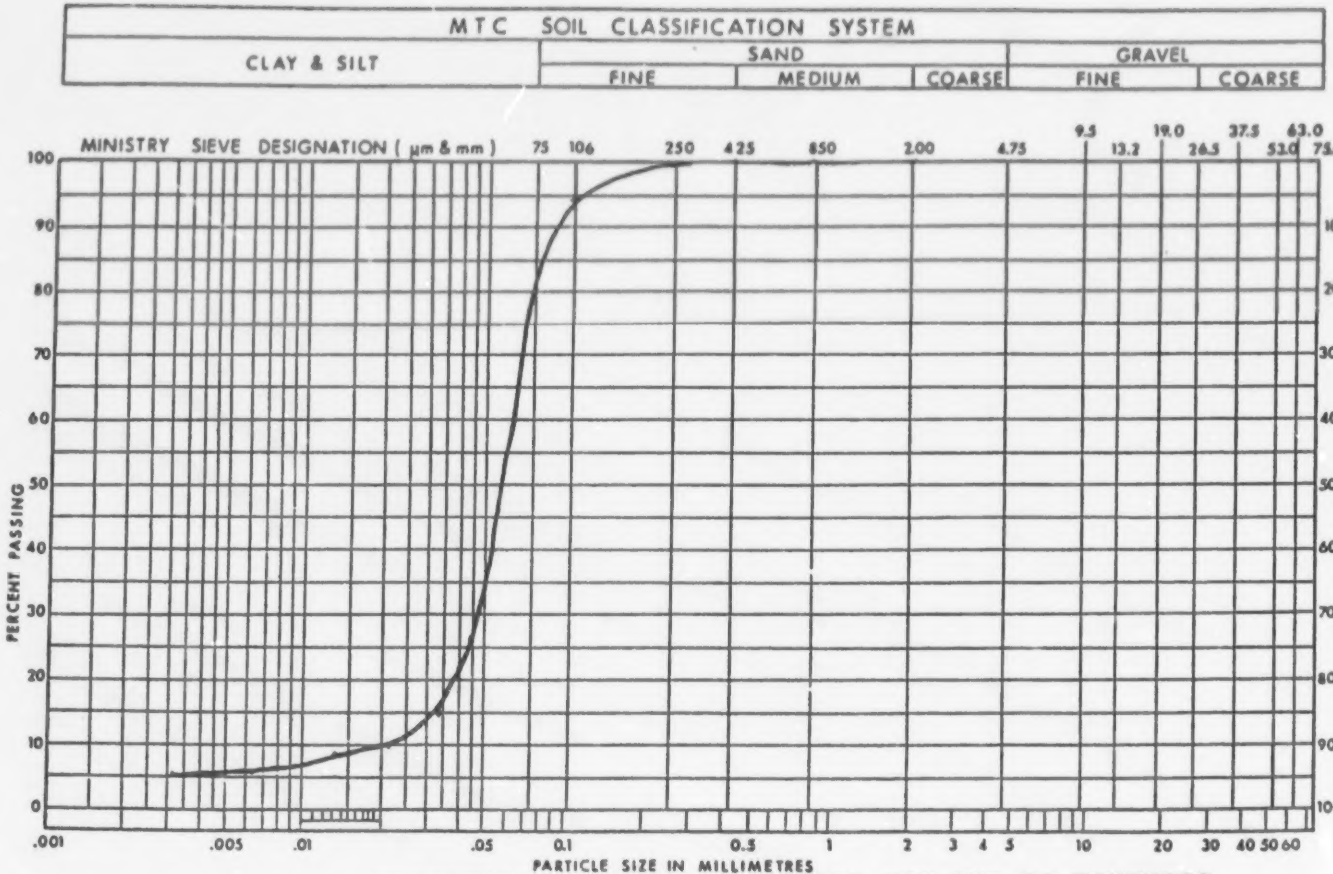
Test Hole No.	Strata Depth (metres)	Soil Description	Laboratory Sample No.	Results of Lab Analysis
T.H. No.7	0 - 0.2	Tps		
	0.2 - 3.0	Br Si Sa - wet @ 2.0 m		
	3.0 - 9.5	Gry Si Cl - wet, firm @8.0 m		
T.H. No.8	0 - 0.2	Tps		
	0.2 - 3.0	Br VF Si Sa		
	3.0 - 5.0	Gry Si Cl - wet		
	5.0 - 8.0	Gry Cl(y) Si	85A0 2023	unsuitable
	8.0 - 9.5	Gry Si Cl - firm @ 9.0 m		
T.H. No.9	0 - 0.2	Tps		
	0.2 - 3.0	Br VF Si Sa		
	3.0 - 9.5	Br Si Cl - firm @ 8.0 m		
T.H. No.10	0 - 0.2	Tps		
	0.2 - 2.0	Br VF Sa		
	2.0 - 9.5	Br Si Cl - wet, firm @ 8.0 m		
T.H. No.11	0 - 0.2	Tps		
	0.2 - 5.0	Br F-VF Sa, wet @ 3.0 m	85A0 2023	unsuitable
	5.0 - 6.0	Br Si Cl with Si Sa layers		
	6.0 - 9.0	Gry Si Cl - wet		
	9.0 - 9.5	Gry Si Cl - firm		
T.H. No.12	0 - 0.2	Tps		
	0.2 - 3.0	Gry Sa Si - wet @ 2.0 m		
	3.0 -11.0	Gry Si Cl - wet		
	11.0 -12.5	Gry Cl Si Till - firm	85A0 2026	unsuitable
T.H. No.13	0 - 0.2	Tps		
	0.2 - 1.5	Br Si VF Sa - wet	85A0 2001	unsuitable
	1.5 - 5.0	Br Sa Si - wet	85A0 2002	unsuitable
	5.0+	Gry Cl Si - wet	85A0 2003	unsuitable
T.H. No.14	0 - 0.2	Tps		
	0.2 - 2.0	Br Si VF Sa		
	2.0 - 9.5	Br Si Cl Till - wet @ 3.0 m -firm @ 8.0 m		

Test Hole No.	Strata Depth (metres)	Soil Description	Laboratory Sample No.	Results of Lab Analysis
T.H. No.15	0 - 0.2	Tps		
	0.2 - 4.3	Br Si VF Sa - wet @ 3.0 m		
	4.3 - 9.5	Br Si Cl - wet, firm @ 9.0 m		
	9.5+	Cl Gr		
T.H. No.16	0 - 0.2	Tps		
	0.2 - 3.0	Br VF Sa, some Si - wet		
	3.0 - 7.0	Br Si Cl - wet		
	7.0 - 8.0	Br Si Sa - wet		
	8.0 - 9.5	Br Si Cl Till		
T.H. No.17	0 - 0.2	Tps		
	0.2 - 6.0	Br Si Cl - wet @ 3.0 m		
	6.0 - 7.8	Br Si Cl - wet, firm		
	7.8 - 9.0	Br Cl Si - wet		
	9.0 - 9.5	Br Si cl - wet, firm		
T.H. No.18	0 - 0.2	Tps		
	0.2 - 6.0	Br F Si Sa		
	6.0 - 9.0	Br Si Cl - wet		
	9.0 - 9.5	Br Si Sa - wet		
T.H.No.19	0 - 0.2	Tps		
	0.2 - 2.0	Br VF Sa - wet		
	2.0 - 4.0	Br VF Si sa - wet		
	4.0 - 9.5	Gry Si(y) Cl - wet, soft		
T.H. No.20	0 - 0.2	Tps		
	0.2 - 7.0	Br Si Cl - wet		
	7.0 - 8.0	Med. Gr - 50% Stn, max. 65 mm		
	8.0+	N.F.P.		
T.H. No.21	0 - 0.2	Tps		
	0.2 - 3.0	Br Si Sa - wet		
	3.0 - 4.0	Br Si Cl - wet		
	4.0 - 4.3	Cl(y) Gr		
	4.3 - 8.0	Br M-F Sa - 20% Stn, water @ 6.0 m	85A0 2019	acceptable
	8.0 - 8.5	Gr VF Sa		
	8.5+	N.F.P.		

Test Hole No.	Strata Depth (metres)	Soil Description	Laboratory Sample No.	Results of Lab Analysis
T.H. No.22	0 - 0.2	Tps		
	0.2 - 3.0	Br F Si Sa		
	3.0 - 4.0	Br Si Cl		
	4.0 -11.0	Br Si F Sa - caving in @ 9.0 m	85A0 2032	borderline acceptable
	11.0 -12.5	Gry F Sa, some Si	85A0 2033	acceptable
T.H. No.23	0 - 0.2	Tps		
	0.2 - 1.0	Br Si Cl		
	1.0 - 3.0	M-F Sa - 10% Stn, 25 mm Max		
	3.0 - 6.0	F Sa - some Si balls	85A0 2015	acceptable
	6.0 - 7.5	Br Si Sa - wet	85A0 2016	unsuitable
	7.5 -10.0	Br Sa Cl - wet		
	10.0 -10.7	Gry M F Sa	85A0 2017	acceptable
T.H. No.24	0 - 0.2	Tps		
	0.2 - 3.5	Br VF Sa - wet @ 2.1 m		
	3.5 - 4.0	Gry Cl(y) Si - wet		
	4.0 -10.7	Gry Si Cl - wet, firm @ 10.0 m		
T.H. No.25	0 - 0.2	Tps		
	0.2 - 3.0	Br Si F Sa - wet	85A0 2013	unsuitable
	3.0 - 5.0	Br Cl(y) Si	85A0 2014	unsuitable
	5.0 - 5.2	Co & M Sa - clean		
	5.2 - 6.5	Br Si Cl -firm		
T.H. No.26	0 - 0.2	Tps		
	0.2 - 1.0	Br Si Sa		
	1.0 - 9.0	Br Si Cl - water @4.0 m	85A0 2004	unsuitable
	9.0 - 9.5	Br Si Cl Till		
T.H. No.27	0 - 0.2	Tps		
	0.2 - 4.0	Br F Sa, some Si	85A0 2015	unsuitable
	4.0 -12.5	Br Cl(y) Si - wet, firm @ 11.0 m	85A0 2016	unsuitable
T.H. No.28	0 - 0.2	Tps		
	0.2 - 3.0	Br F-VF Sa - wet	85A0 2005	unsuitable
	3.0 - 6.0	Gry Si Cl - wet		

Test Hole No.	Strata Depth (metres)	Soil Description	Laboratory Sample No.	Results of Analysis
T.H. No.29	0 - 0.2	Tps		
	0.2 - 3.5	Br F-VF Sa - wet @2.0m	85A0 2006	unsuitable
	3.5 - 4.0	Br F-VF Sa	85A0 2007	unsuitable
	4.0 - 5.5	Br Si Cl - wet		
	5.5 - 6.0	Br Si F Sa - wet	85A0 2008	unsuitable
T.H. No.30	0 - 0.2	Tps		
	0.2 - 1.2	Br Sa Si		
	1.2 - 3.5	Br Si Cl		
	3.5 - 5.5	Br Cl(y) Si - wet @4.0m	85A0 2009	unsuitable
	5.5 - 6.0	Br Sa Si	85A0 2010	unsuitable
	6.0+	Br Si Cl		
T.H. No.31	0 - 0.2	Tps		
	0.2 - 5.0	Br Si Cl - wet		
	5.0 - 6.0	Br Si Sl Till - firm		
	6.0 - 6.3	F Gr		
	6.3 - 6.5	Br Si Cl Till		
T.H. No.32	0 - 0.2	Tps		
	0.2 - 4.0	Br VF Sa - wet @ 3.0 m		
	4.0 - 4.5	Gry Cl(y) Si Till - dry & hard	85A0 2031	unsuitable
	4.5 -12.5	Br Si Cl		
T.H. No.33	0 - 0.2	Tps		
	0.2 - 7.0	Br Si Cl - wet @ 3.0 m	85A0 2029	unsuitable
	7.0 - 8.0	Cl(y) Gran. 50% Stn, max. 65 mm	85A0 2030	incomplete analysis
	8.0+	N.F.P. - cannot lift or list		
T.H. No.34	0 - 0.2	Tps		
	0.2 - 5.0	Si Sa - Max 65 mm	85A0 2027	unsuitable
	5.0 - 6.0	Br Si Cl		
	6.0 - 9.0	Med. Gran - Sat, 55% Stn, max. 75 mm Med. Sa	85A0 2028	borderline for Granular A & B
	9.0+	N.F.P. - cannot lift or list		

T.H. Nº 13 (0.2-1.5m)
85 A0 2001



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 80%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR VF. SI. SA WI-T.
LAB Si' SA.

DENSITY

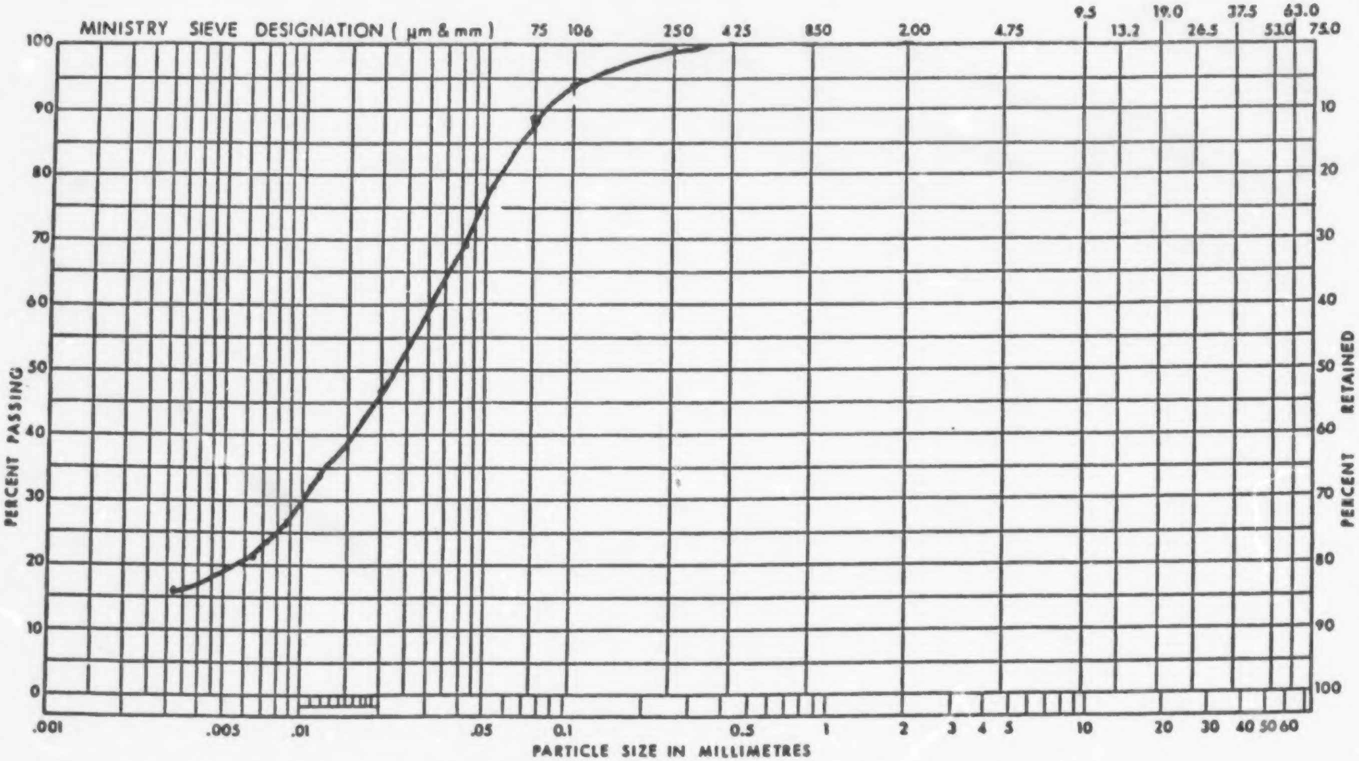
RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 26.2 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 36%
% 5 - 106 µm 88%
FROST SUSCEPTIBILITY

T.H. Nº 13 (1.5-5.0 m)
85A0 2002

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%

% PASSING 75 µm 88%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR-SA.SI. WET

LAB SA. Si.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 24.1 %

% COMPACTION

SILT.

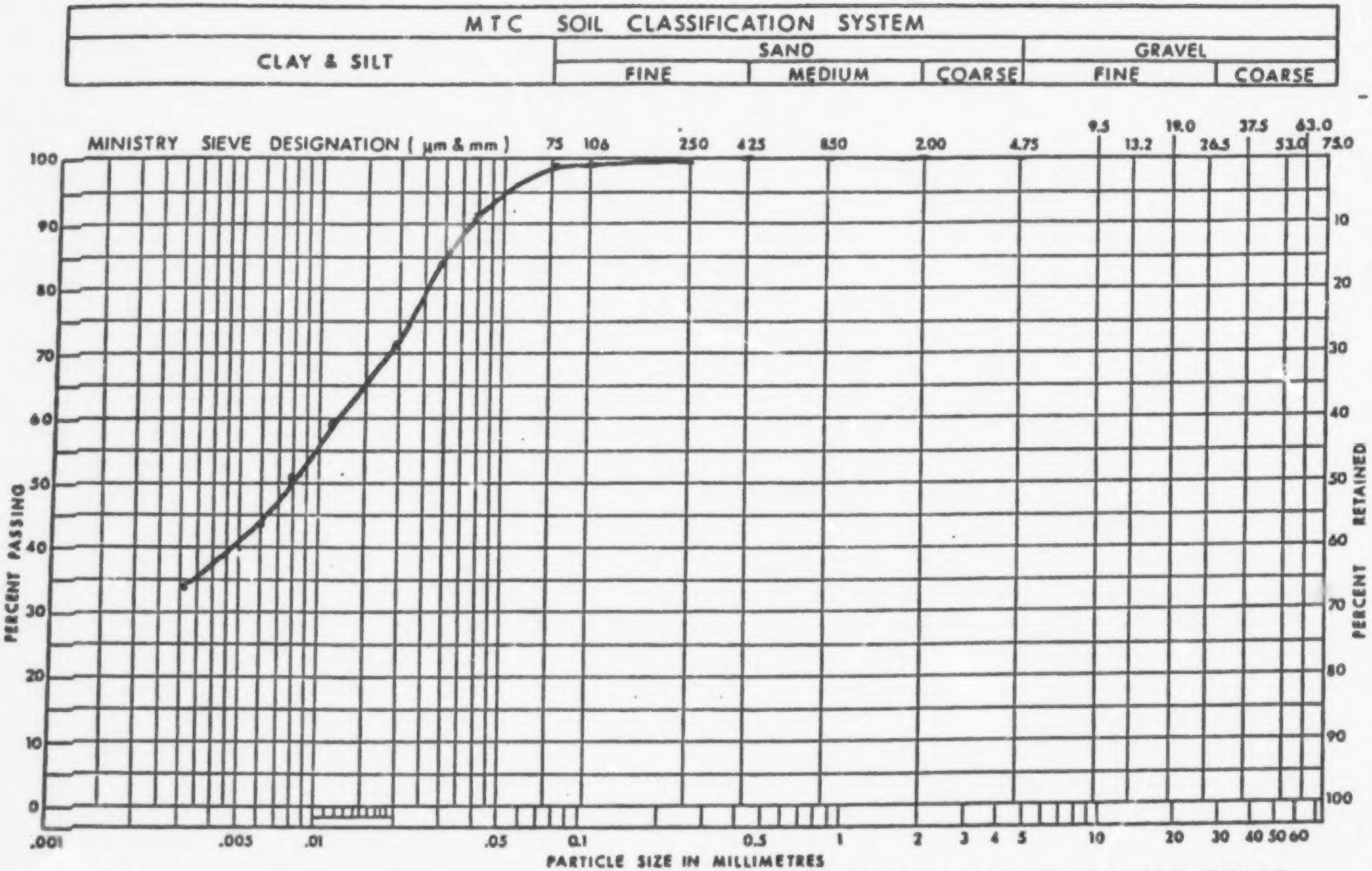
FROST CRITERIA

% 5 - 53 µm 59%

% 5 - 106 µm 75%

FROST SUSCEPTIBILITY

T.H. Nº 13 (5,0m+)
85A0 2003



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm

% PASSING 75 μm 99%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD Grey Silt. wet.

LAB Ch. Si.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 26.8 %

% COMPACTION

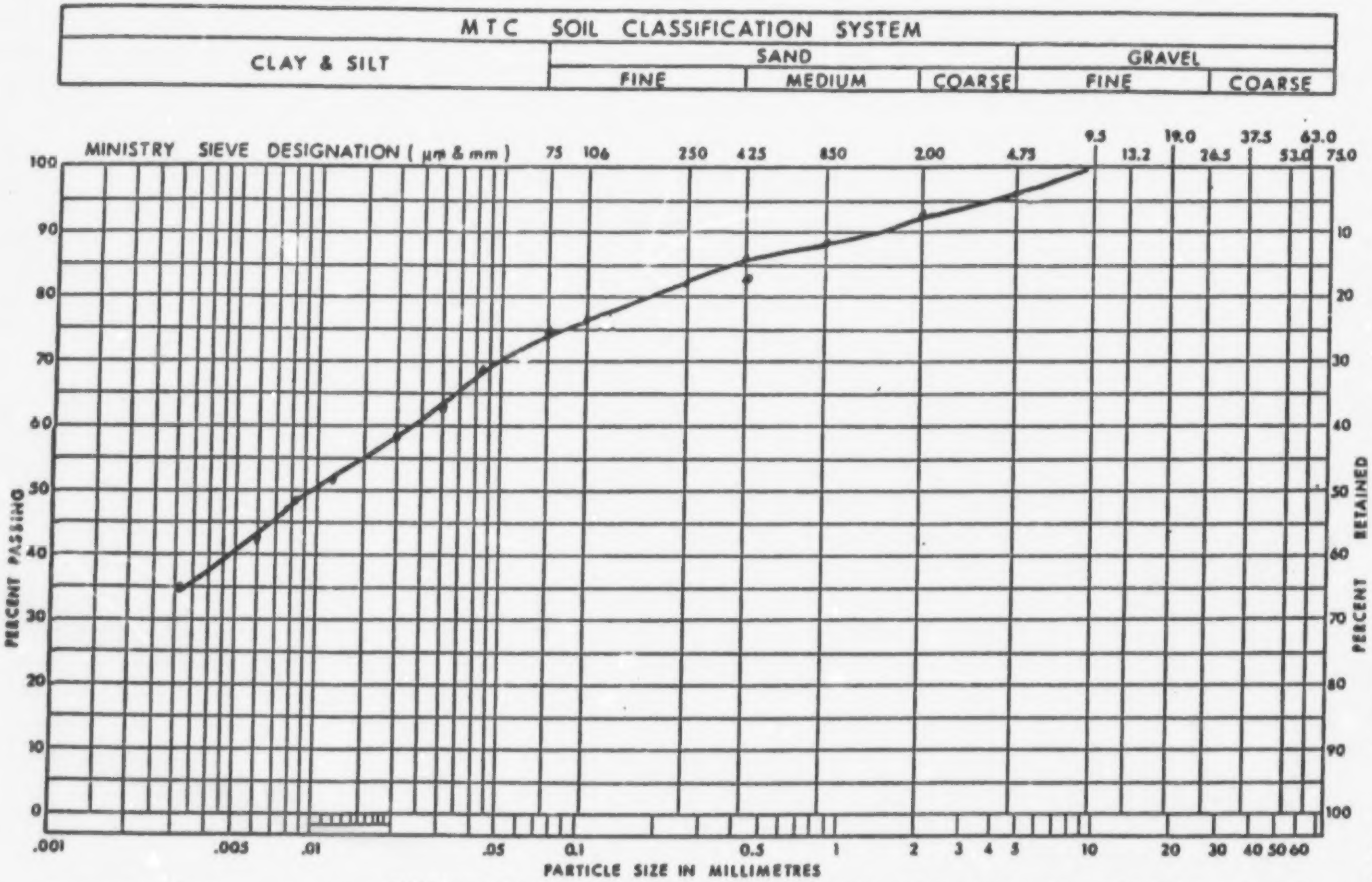
FROST CRITERIA

% 5 - 53 μm 56%

% 5 - 106 μm 58%

FROST SUSCEPTIBILITY

T.H. Nº 26 (1.0-9.0m)
85 A O 2004



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 76 %
% PASSING 75µm 75%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD Gr. Si. CL.

LAB Si. Cl.

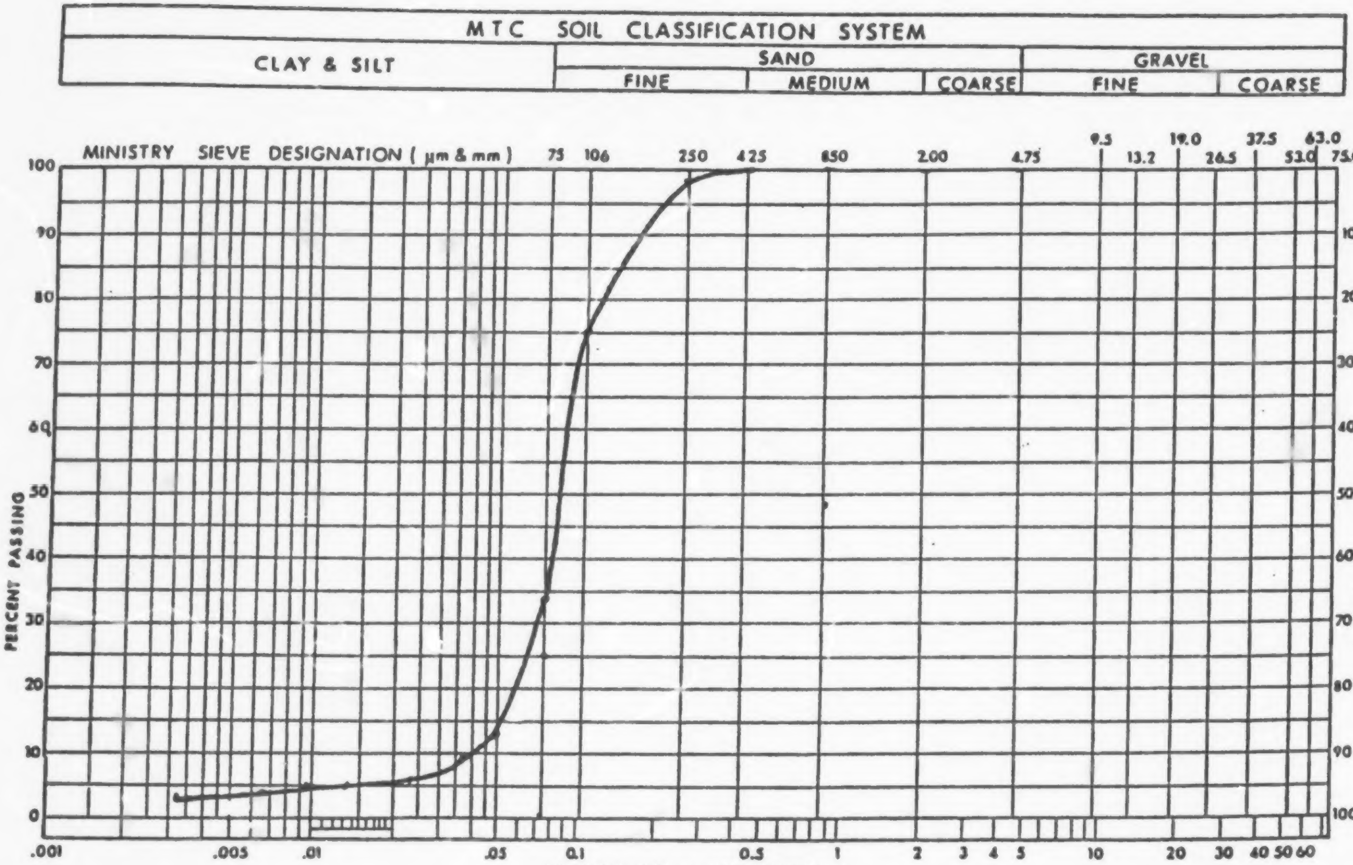
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 17.7 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 31%
% 5 - 106 µm 36%
FROST SUSCEPTIBILITY

T.H. Nº 28 (02-3.0m)
85 A O 2005



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 34%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) _____ %
PLASTIC LIMIT (W_P) _____ %
PLASTICITY INDEX (I_P) _____ %

CLASSIFICATION & GROUP SYMBOL

FIELD GR. VF. SI. SA Lx-T.

LAB F-VF SA.

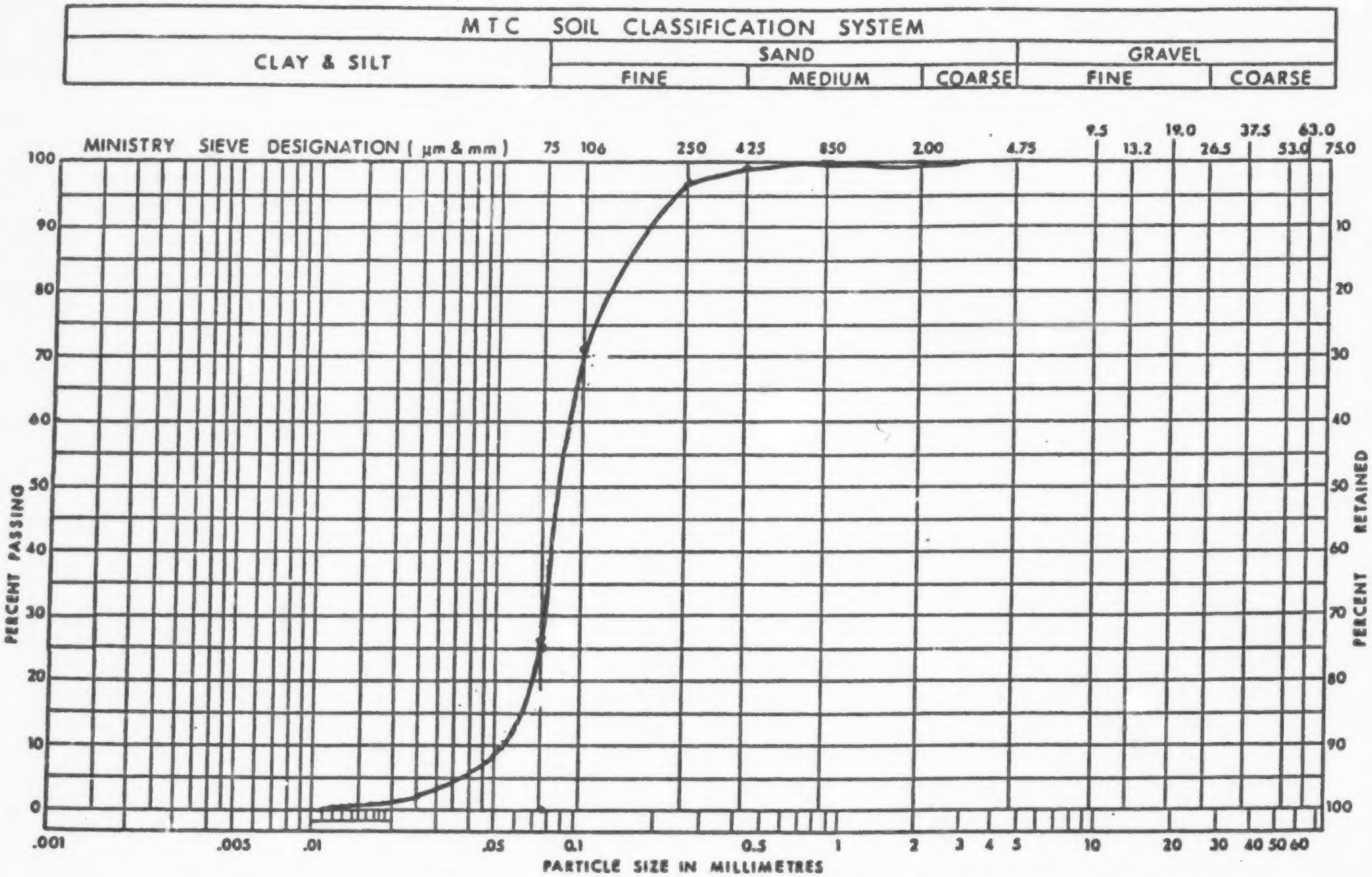
DENSITY

RELATIVE DENSITY
MAXIMUM WET _____ t/m³
MAXIMUM DRY _____ t/m³
OPTIMUM MOISTURE CONTENT _____ %
FIELD WET _____ t/m³
FIELD DRY _____ t/m³
FIELD MOISTURE CONTENT 24.0 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 10%
% 5 - 106 µm 72%
FROST . SUSCEPTIBILITY

T.H. Nº 29 (0.2-3.5 m)
85A0 2006



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 27%.
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR. VF. SA WET.
LAB F. SA.

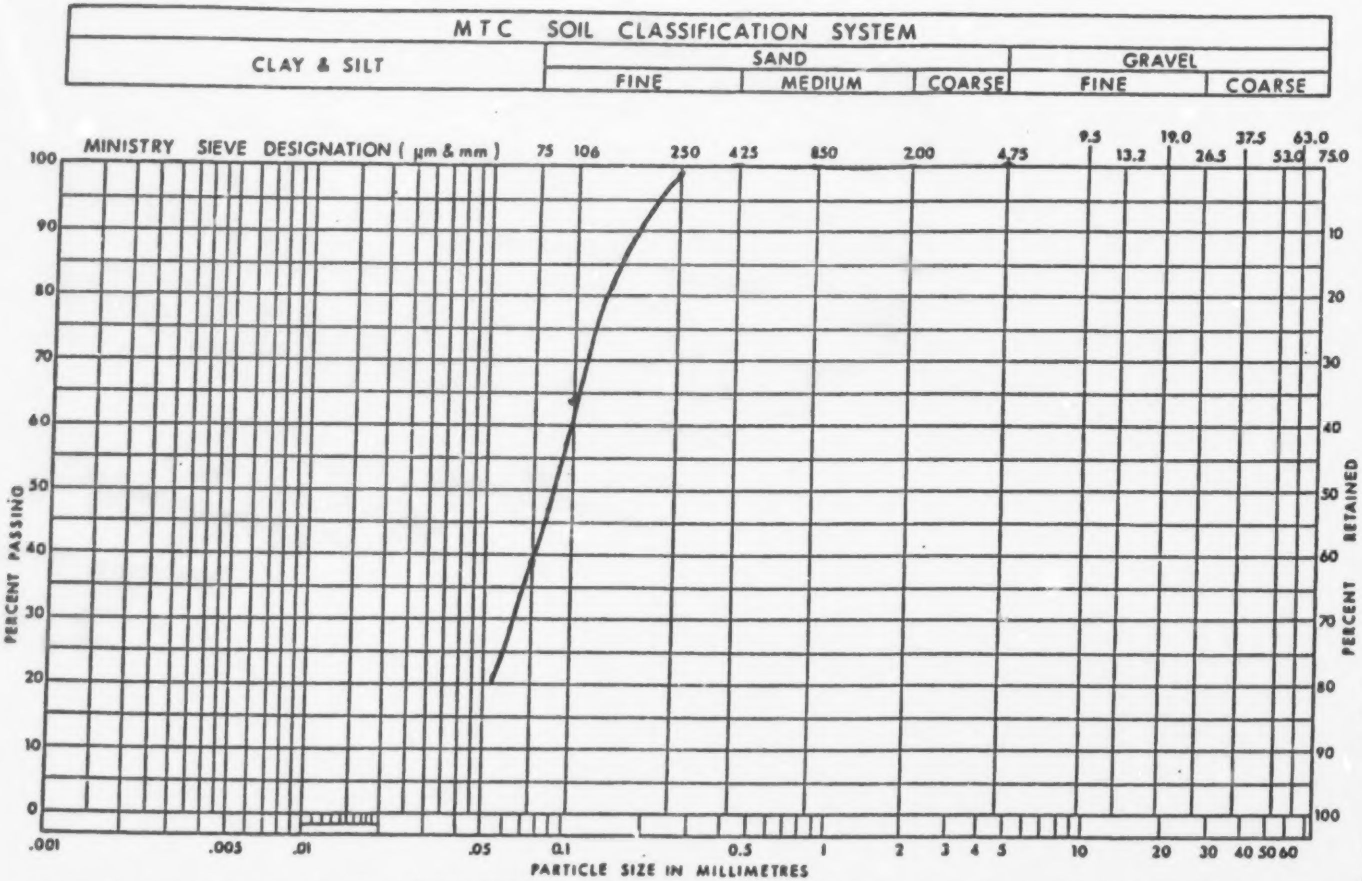
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 11.6 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 9
% 5 - 106 µm 70
FROST SUSCEPTIBILITY

T.H. Nº 29 (3.5-4.0m)
85A0 2007



SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75µm 39%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR. VF. SA WET.
LAB F. VF. SA.

DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 26.9 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 15
% 5 - 106 µm
FROST SUSCEPTIBILITY

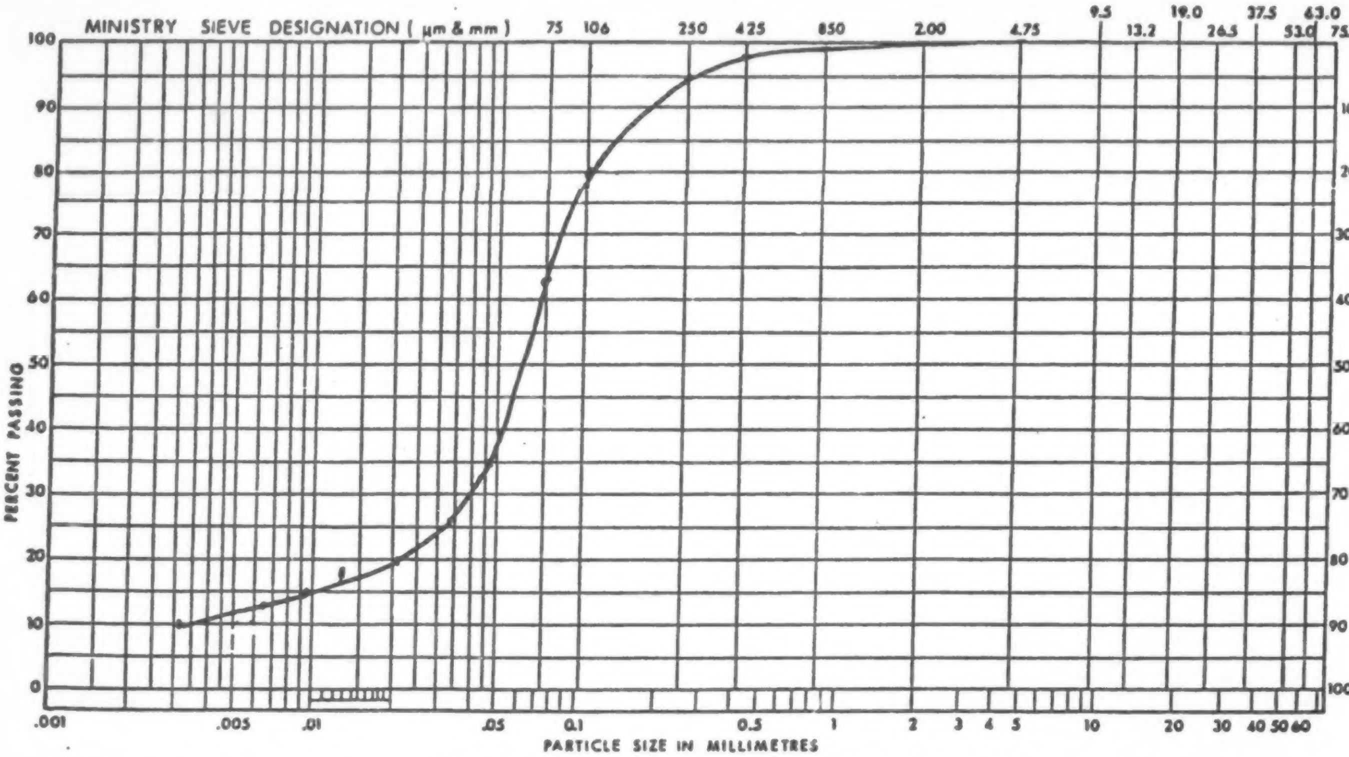
REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINENESS

DATE 86 04 10

SIGNATURE

T.H. Nº 29 (5.5-6.0m)
85A0 2008

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 63%.
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BE. F-VF. SA WL:1.
LAB Si. SA.

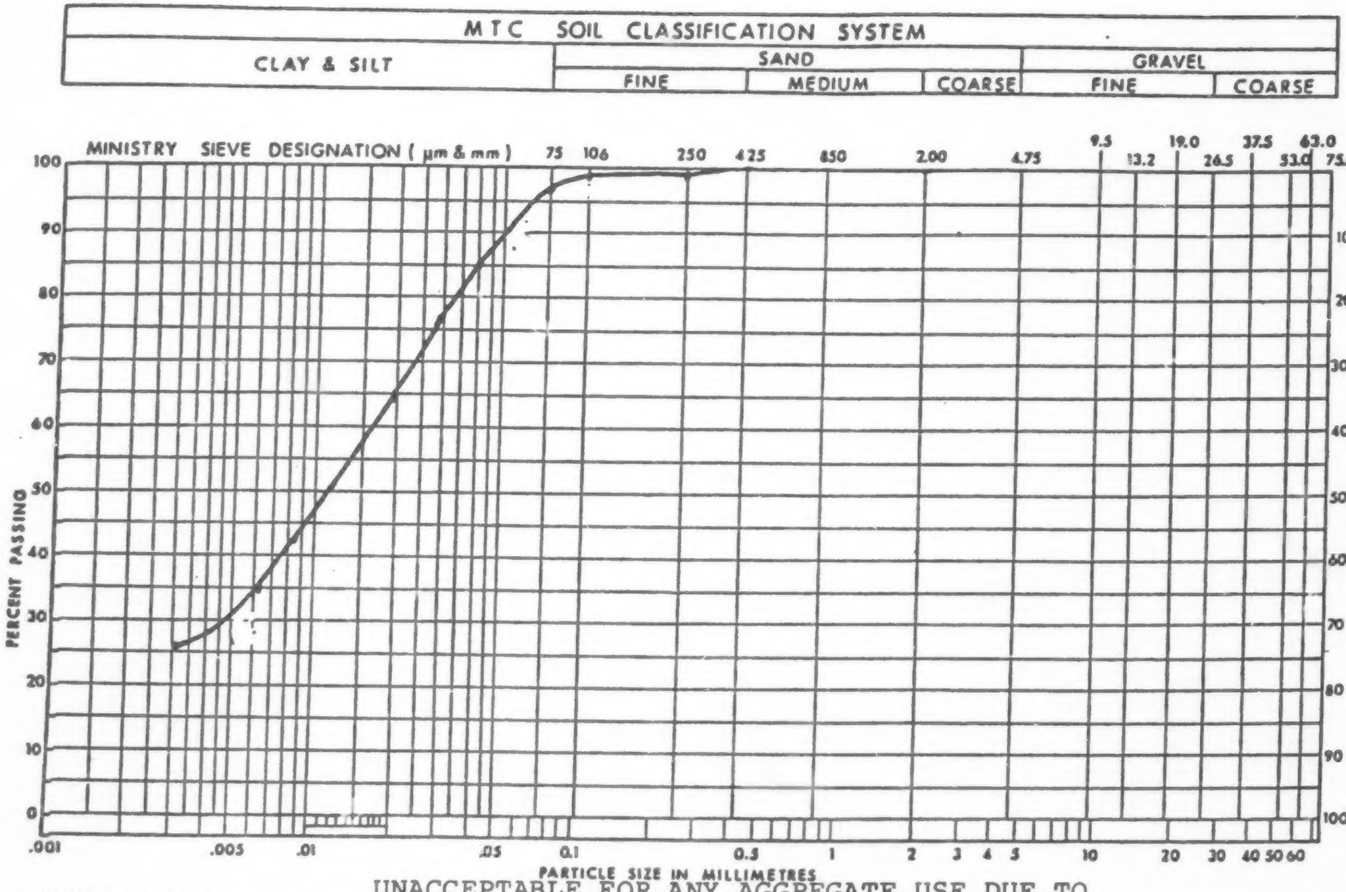
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 25.0 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 28%
% 5 - 106 µm 68%
FROST SUSCEPTIBILITY

T.H. Nº 30 (3.5-5.5m)
85A0 2009



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 μm 97%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \cdot D_{60}} =$
LIQUID LIMIT (W_L) ____ %
PLASTIC LIMIT (W_P) ____ %
PLASTICITY INDEX (I_P) ____ %

CLASSIFICATION & GROUP SYMBOL

FIELD Br. CL. Si.
LAB CL.Si.

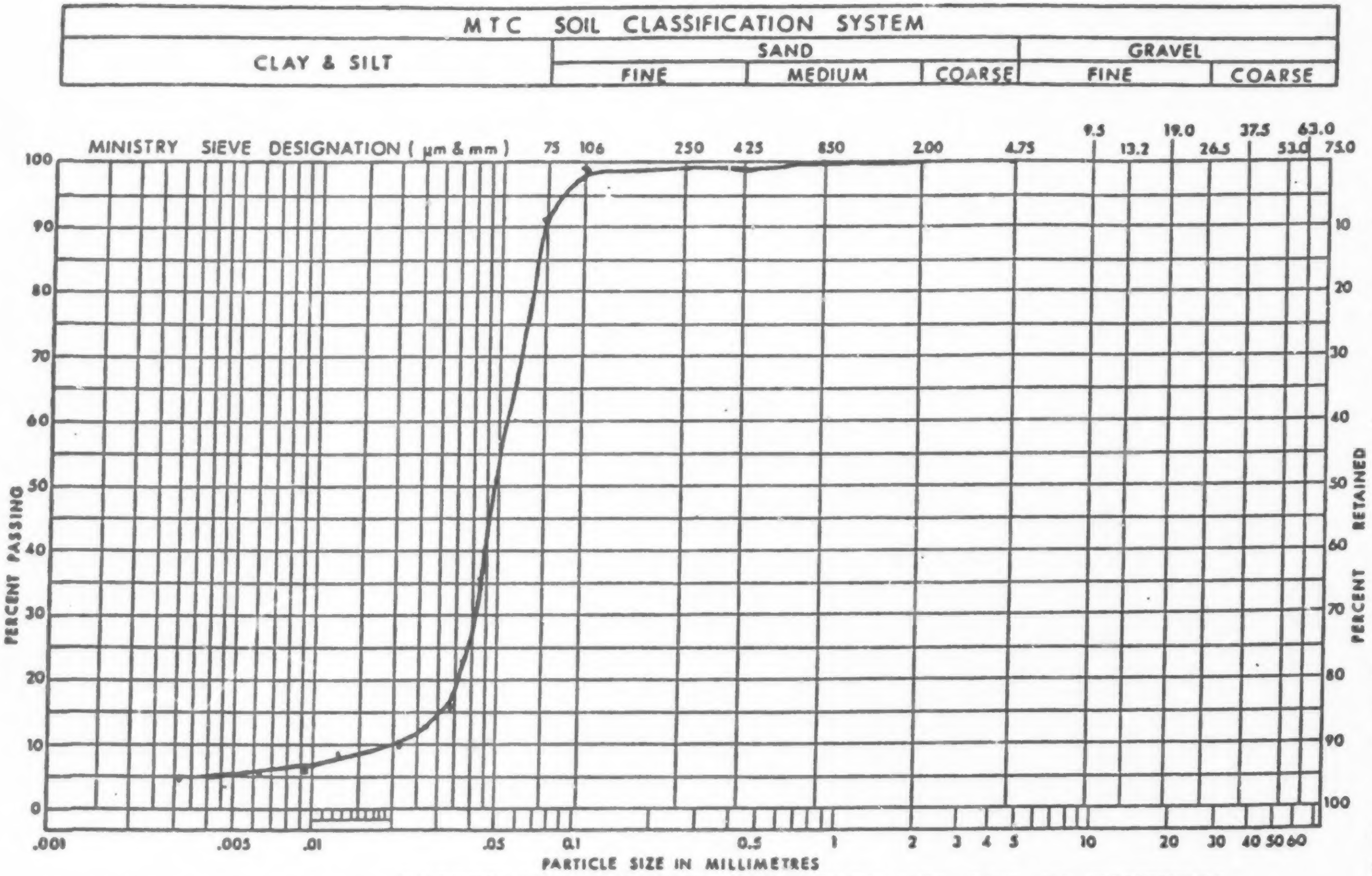
DENSITY

RELATIVE DENSITY ____
MAXIMUM WET ____ t/m³
MAXIMUM DRY ____ t/m³
OPTIMUM MOISTURE CONTENT ____ %
FIELD WET ____ t/m³
FIELD DRY ____ t/m³
FIELD MOISTURE CONTENT 17.1 %
% COMPACTION ____

FROST CRITERIA

% 5 - 53 μm 60%
% 5 - 106 μm 67%
FROST SUSCEPTIBILITY ____

T.H. Nº 30 (5.5-6.0 m)
85 A O 2010



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 91%
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L)
PLASTIC LIMIT (W_P)
PLASTICITY INDEX (I_P)

CLASSIFICATION & GROUP SYMB

FIELD BRAVF SF

LAB SA-Si.

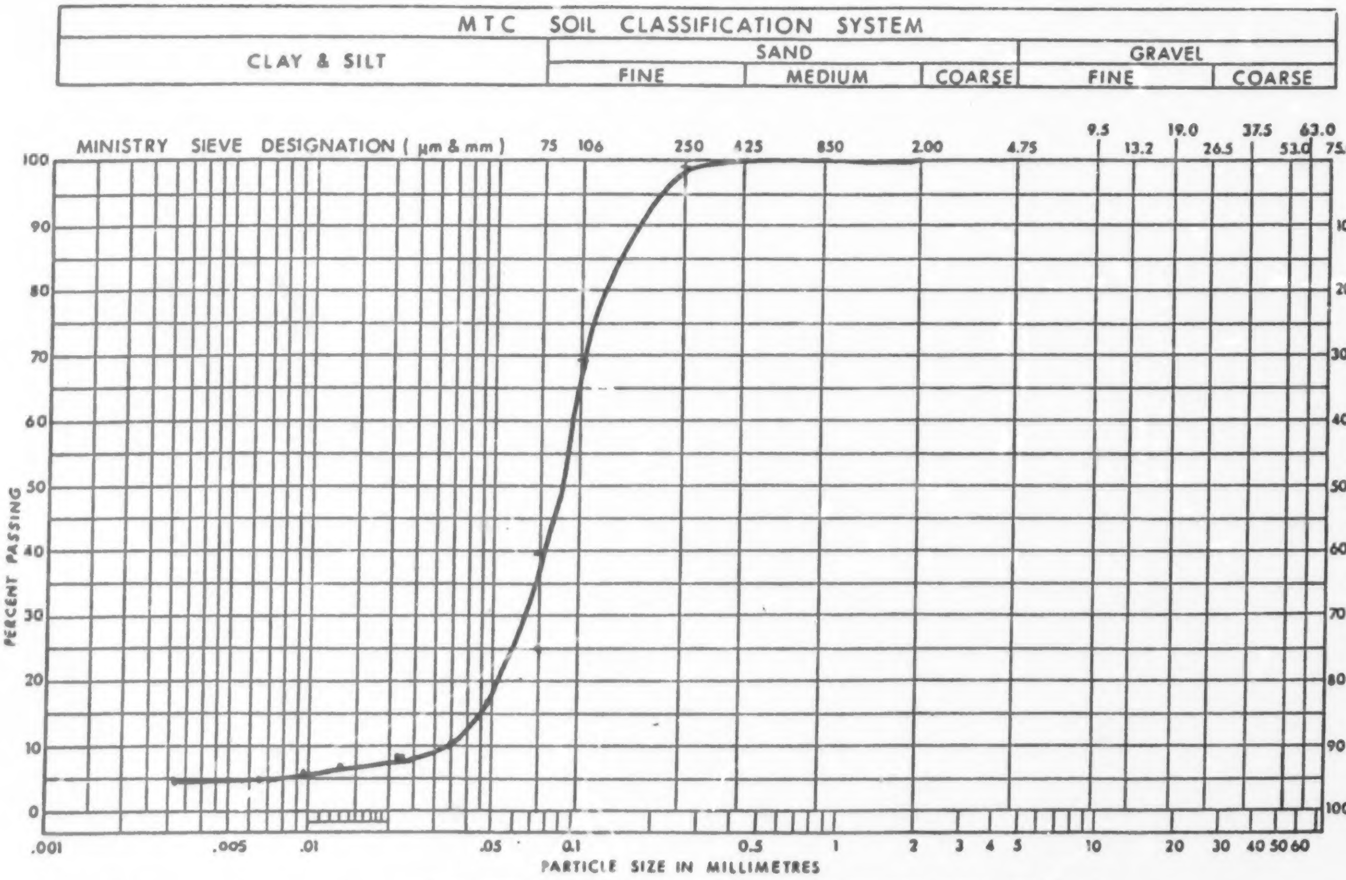
DENSITY

RELATIVE DENSITY
MAXIMUM WET
MAXIMUM DRY
OPTIMUM MOISTURE CONTENT
FIELD WET
FIELD DRY
FIELD MOISTURE CONTENT 23%
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 58%
% 5 - 106 µm 93%
FROST SUSCEPTIBILITY

T.H. Nº 27 (0.2-4.0m)
85 AO 2011



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINENESS

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%

% PASSING 75 µm 39%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB F. SAND. (Si. SA.)

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 25.1 %

% COMPACTION

FROST CRITERIA

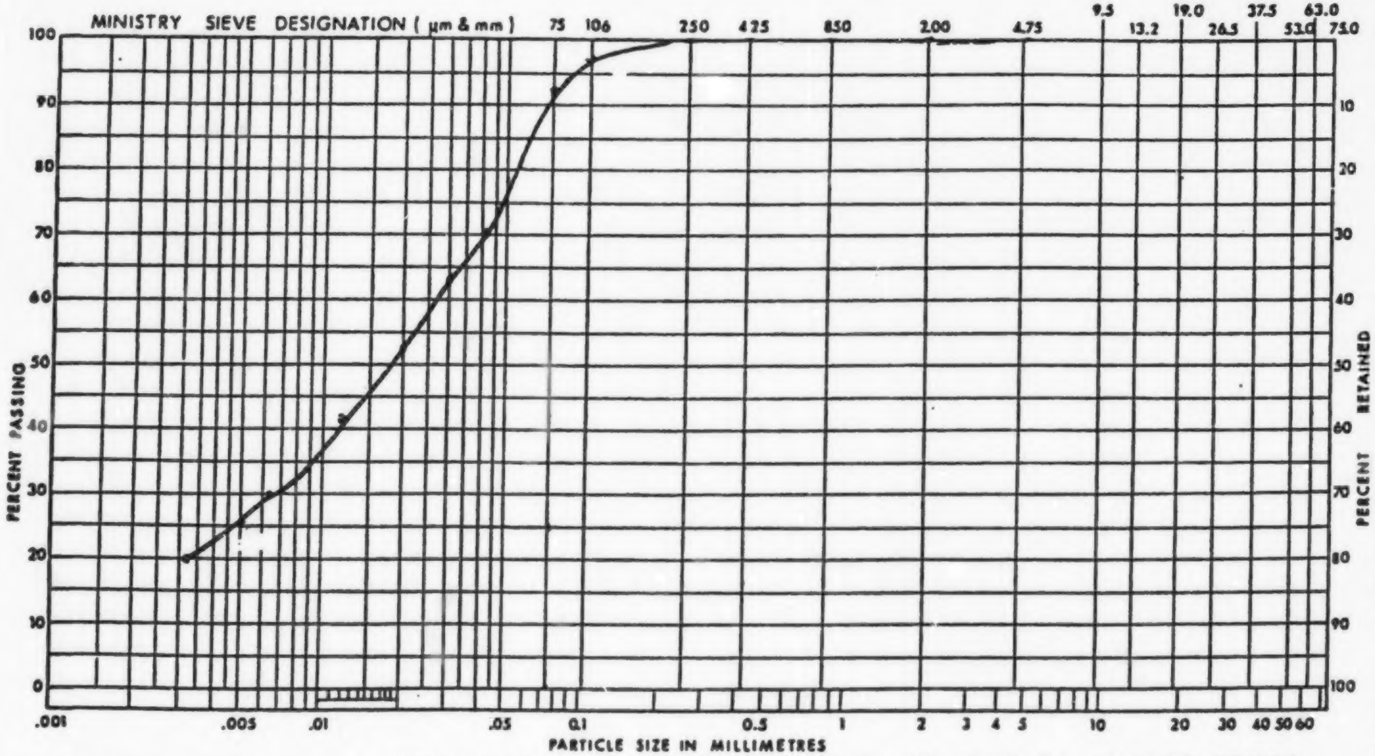
% 5 - 53 µm 17%

% 5 - 106 µm 64%

FROST SUSCEPTIBILITY

T.H. Nº 27 (4.0-125m)
85A0 2012

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%

% PASSING 75 µm 93%.

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB Cl. Si.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 24.8 %

% COMPACTION

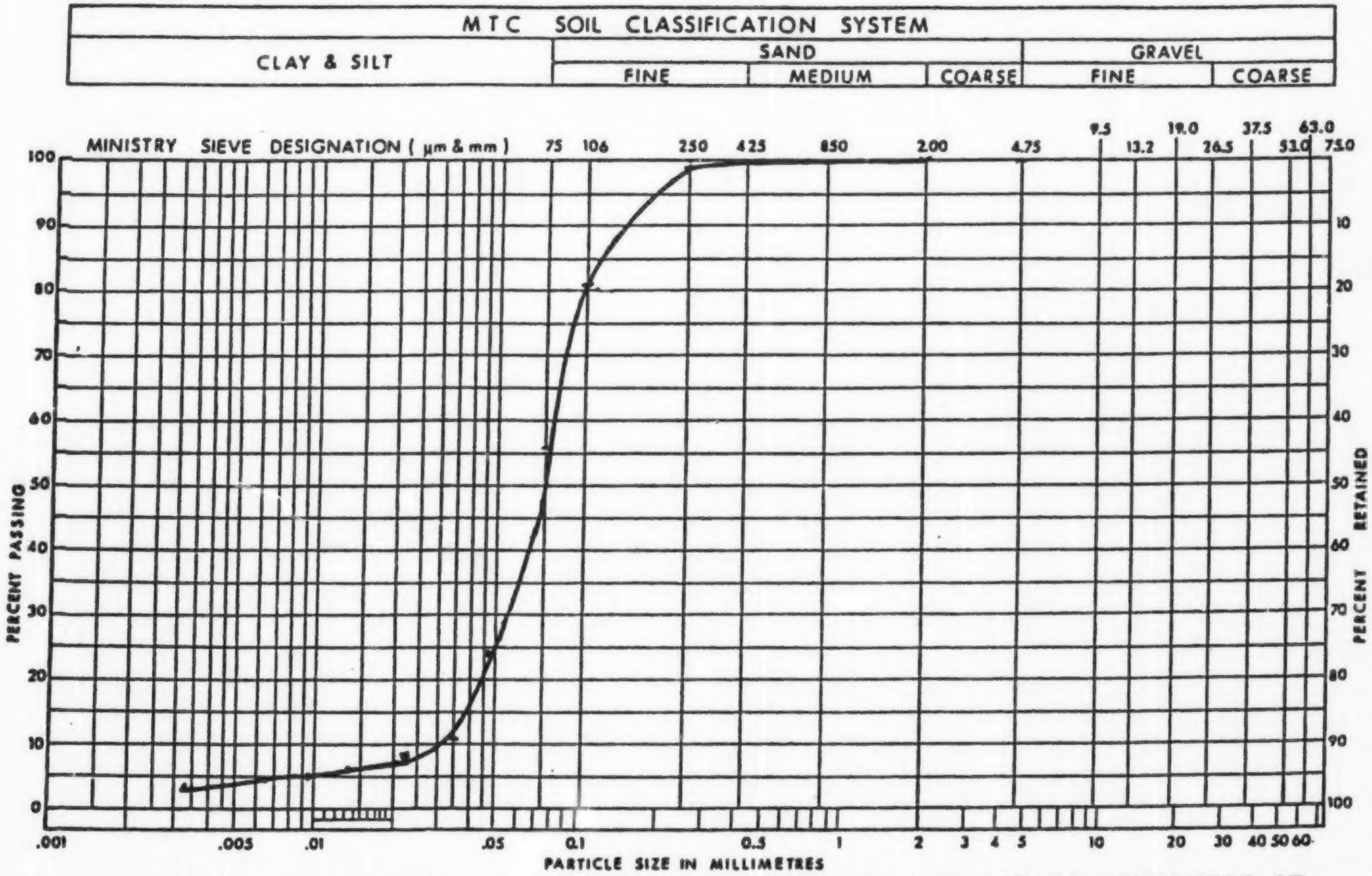
FROST CRITERIA

% 5 - 53 µm 56%

% 5 - 106 µm 71%

FROST SUSCEPTIBILITY

T.H. Nº 25 (0.2-3.0m)
85 A0 2013



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS OF FINENESS

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100 %
% PASSING 75 µm 56 %
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB Si. SA.

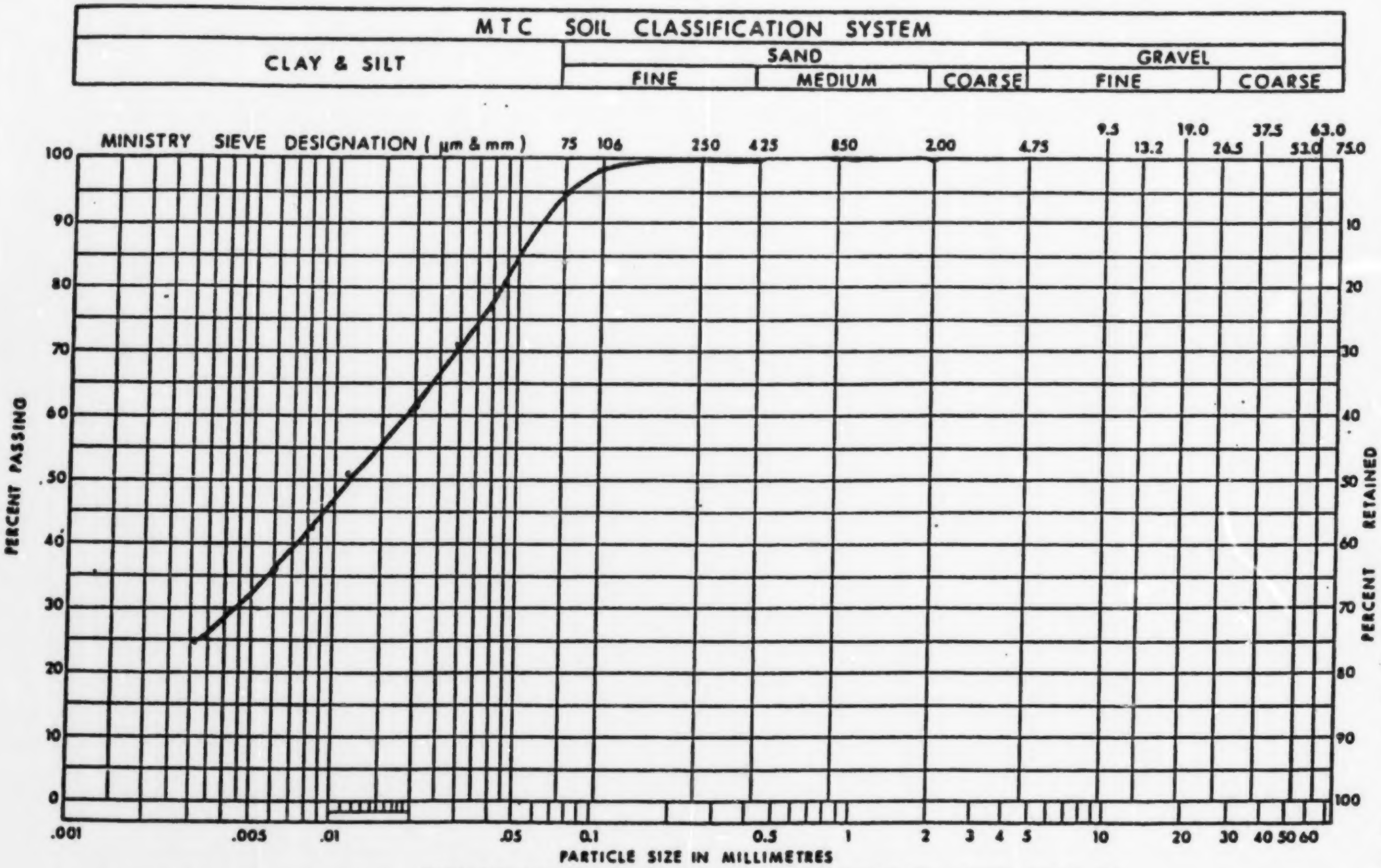
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 22.7 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 25 %
% 5 - 106 µm 77 %
FROST SUSCEPTIBILITY

T.H. Nº 25 (3.0-5.0m)
85 A0 2014



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 95%.
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX(I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB CL. Si.

DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 19.8 %
% COMPACTION

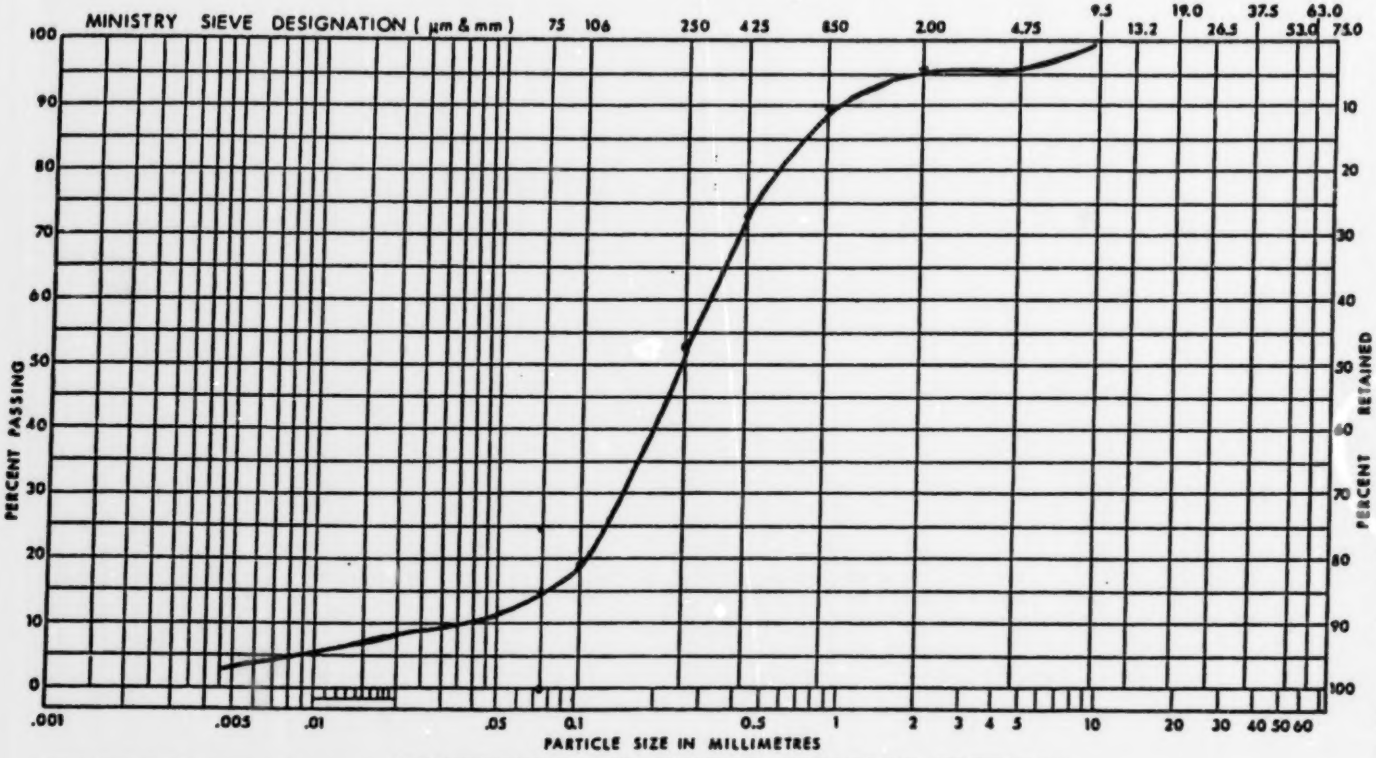
FROST CRITERIA

% 5 - 53 µm 54%
% 5 - 106 µm 65%
FROST SUSCEPTIBILITY

T.H. Nº 23 (3.0-6.0m)
85A0 2015

MTC SOIL CLASSIFICATION SYSTEM

CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS ACCEPTABLE FOR SELECT SUBGRADE MATERIAL

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 96%

% PASSING 75 µm 15%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD Gr. F. SA some [illegible]

LAB F. SAND

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 7.9 %

% COMPACTION

FROST CRITERIA

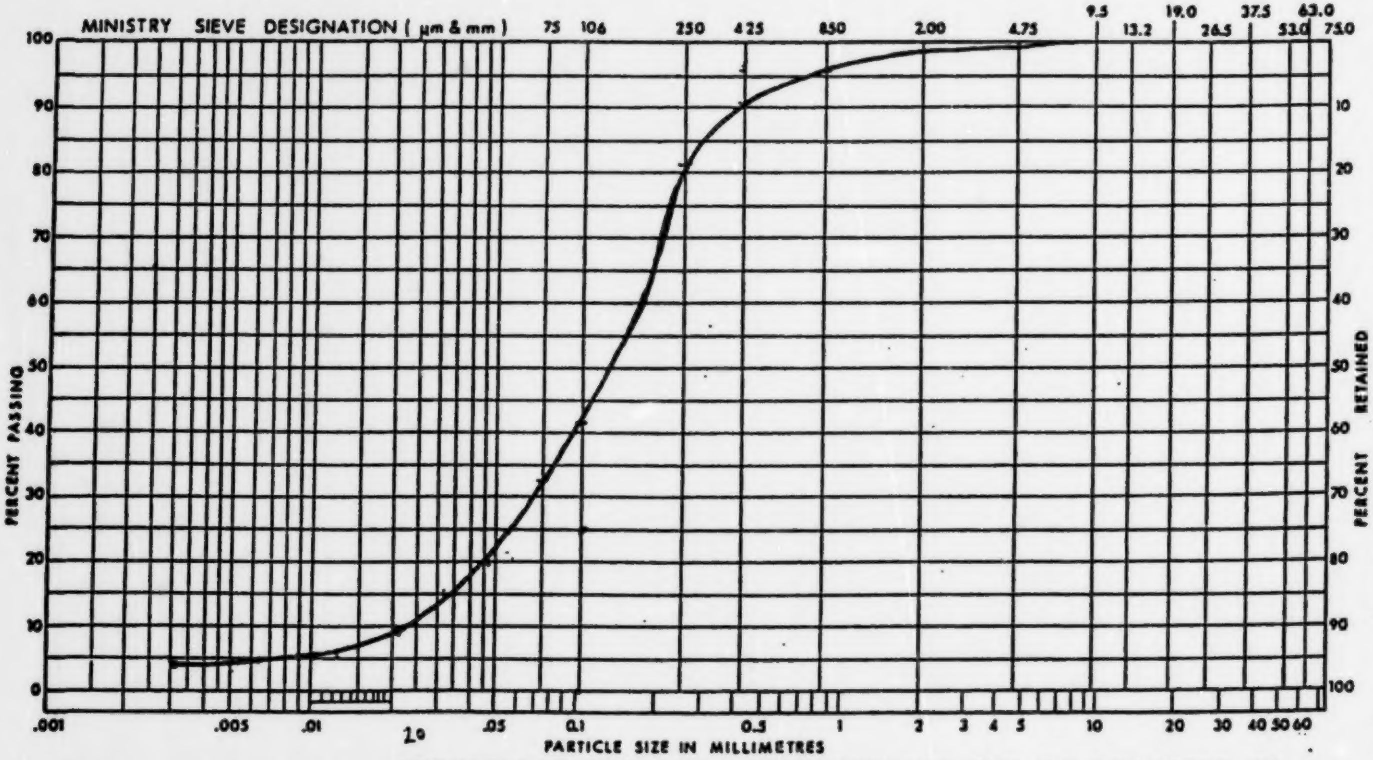
% 5 - 53 µm 5

% 5 - 106 µm 16

FROST SUSCEPTIBILITY

T.H. Nº 23 (6.0-7.5m)
85 AO 2016

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNSUITABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 99 %
% PASSING 75µm 33 %
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W$_L$) %
PLASTIC LIMIT (W$_P$) %
PLASTICITY INDEX(I$_P$) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB Si. SA.

DENSITY

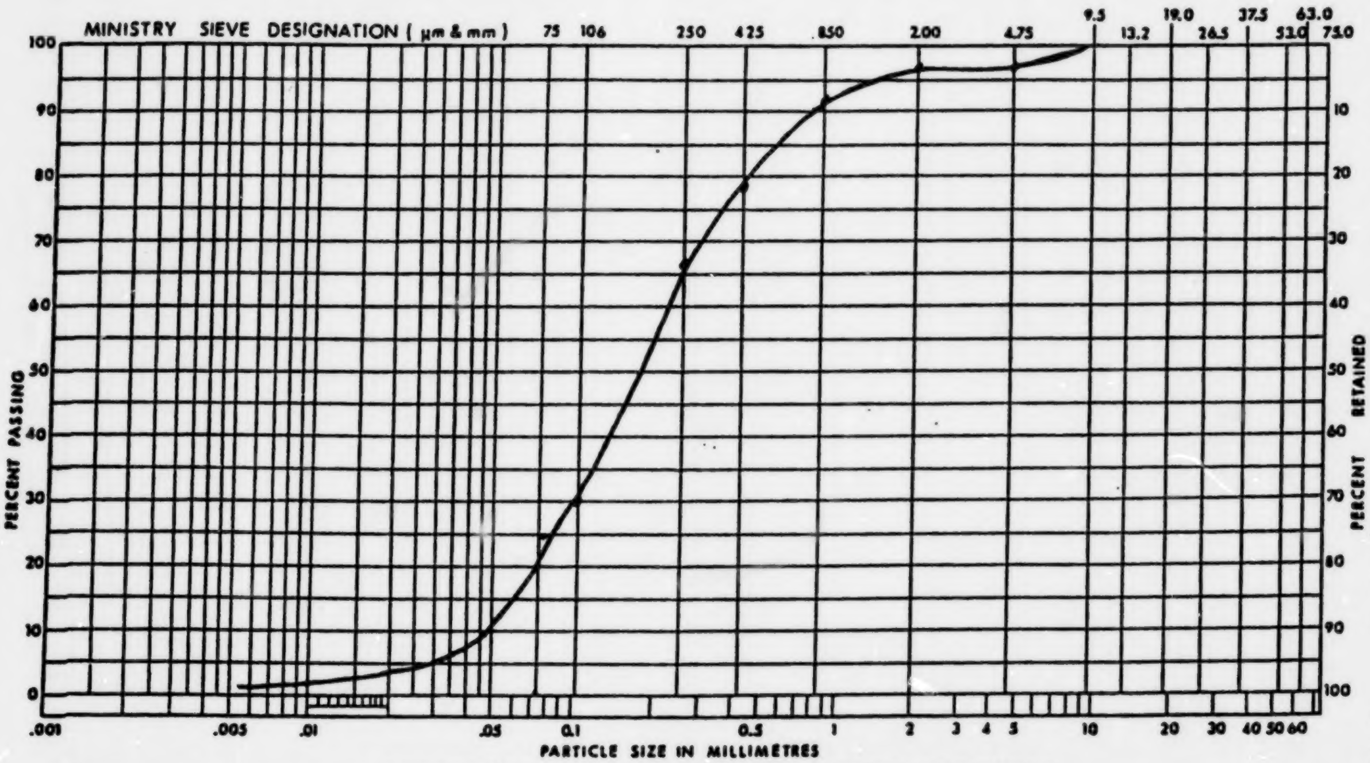
RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 17.3 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 20%
% 5 - 106 µm 38%
FROST SUSCEPTIBILITY

T.H. Nº23 (10.0-10.7m)
85AO 2017

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS ACCEPTABLE FOR SELECT SUBGRADE MATERIAL

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 97%
% PASSING 75µm 20%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX(I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD Br. F.M. SAND

LAB F. SAND.

DENSITY

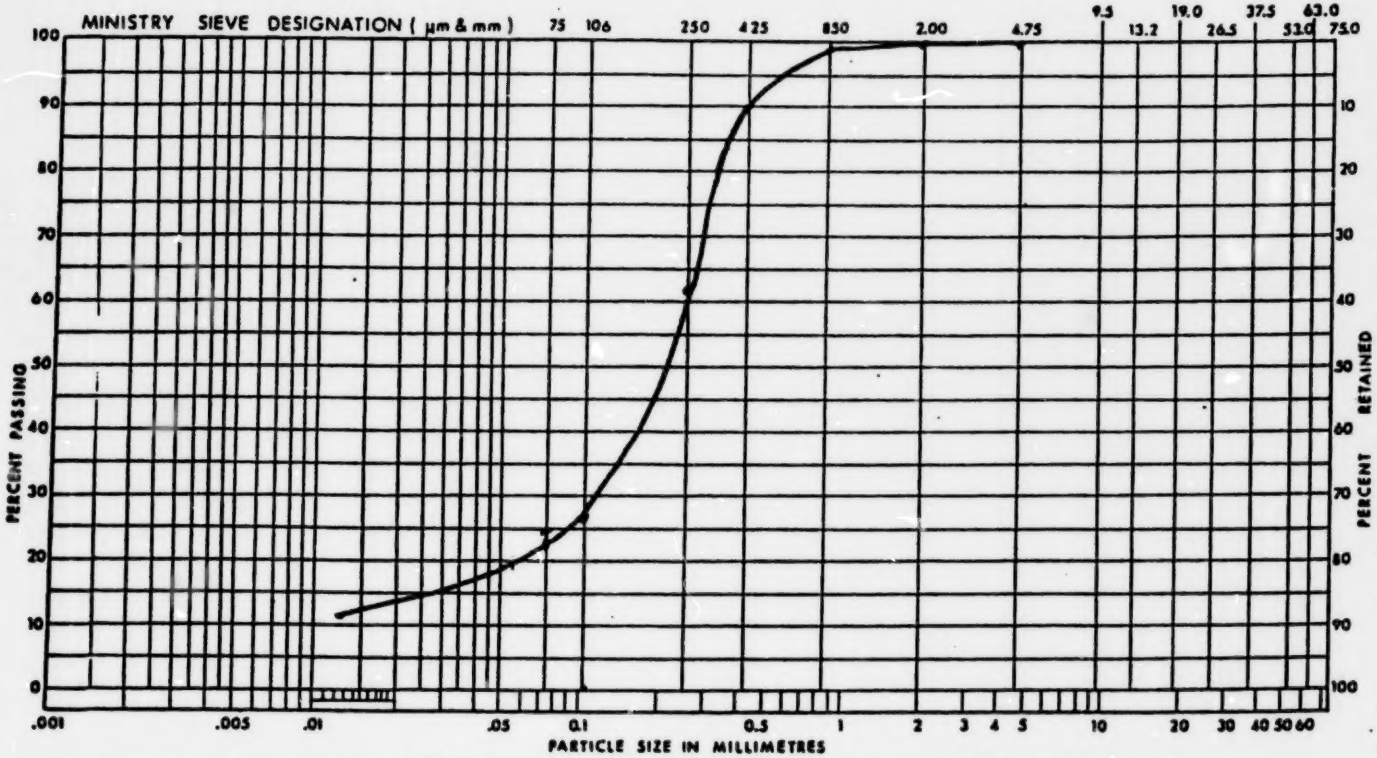
RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 18.3 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 11
% 5 - 106 µm 19
FROST SUSCEPTIBILITY

T.H. Nº11A. (4.0-10.7m)
85 A O 2018

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS ACCEPTABLE FOR SELECT SUBGRADE MATERIAL

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100 %
% PASSING 75µm 23 %.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX(I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR. F. SA Some- Silt bands

LAB F. SAND. - S.SA

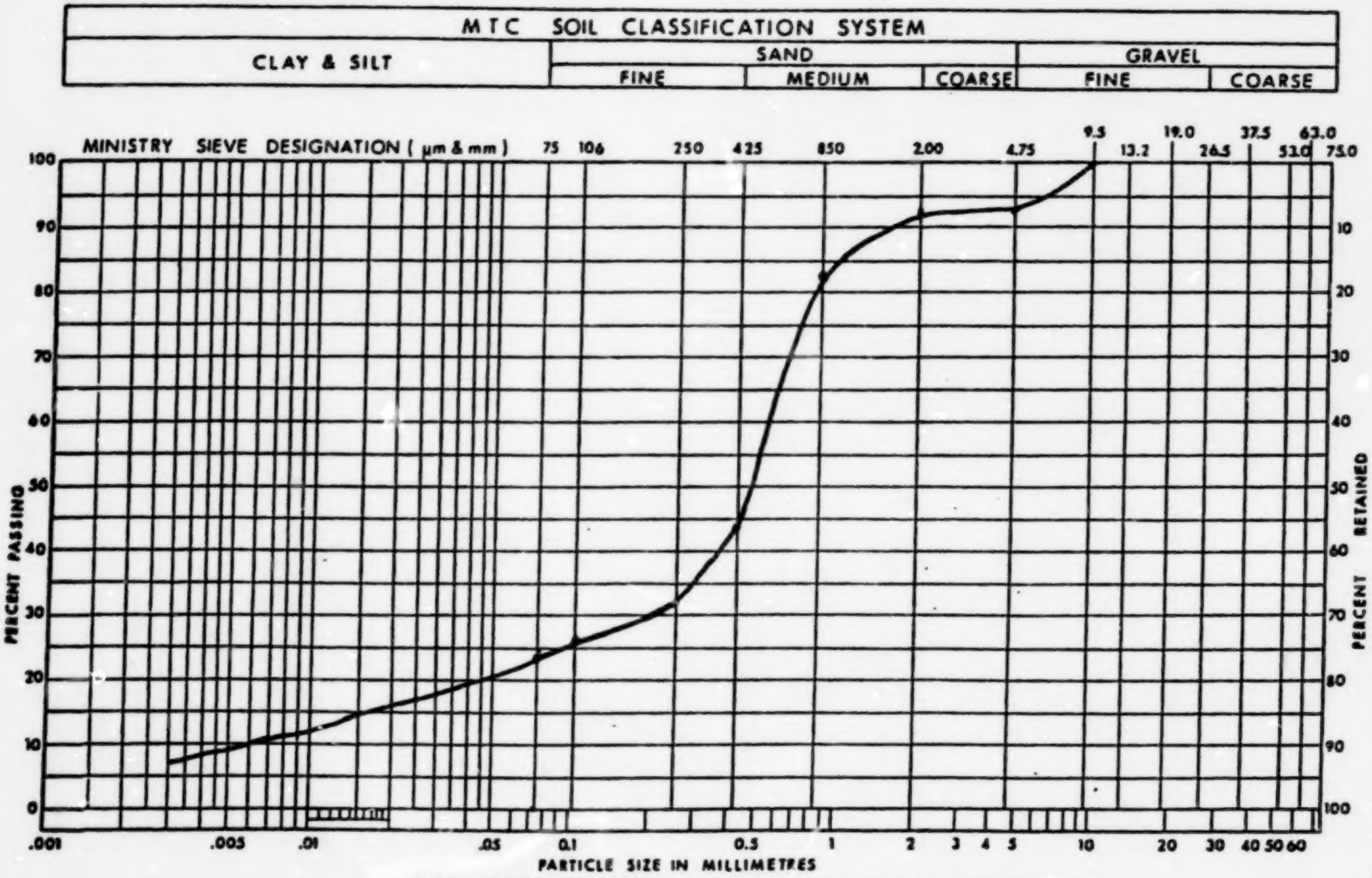
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 14
% 5 - 106 µm 21
FROST SUSCEPTIBILITY

T.H. Nº 21 (4.3-8.0m)
85A0 2019



REMARKS & RECOMMENDATIONS ACCEPTABLE FOR SELECT SUBGRADE MATERIAL

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 93%
% PASSING 75µm 24%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD BR. M-F. SA

LAB M.-F. SAND.

DENSITY

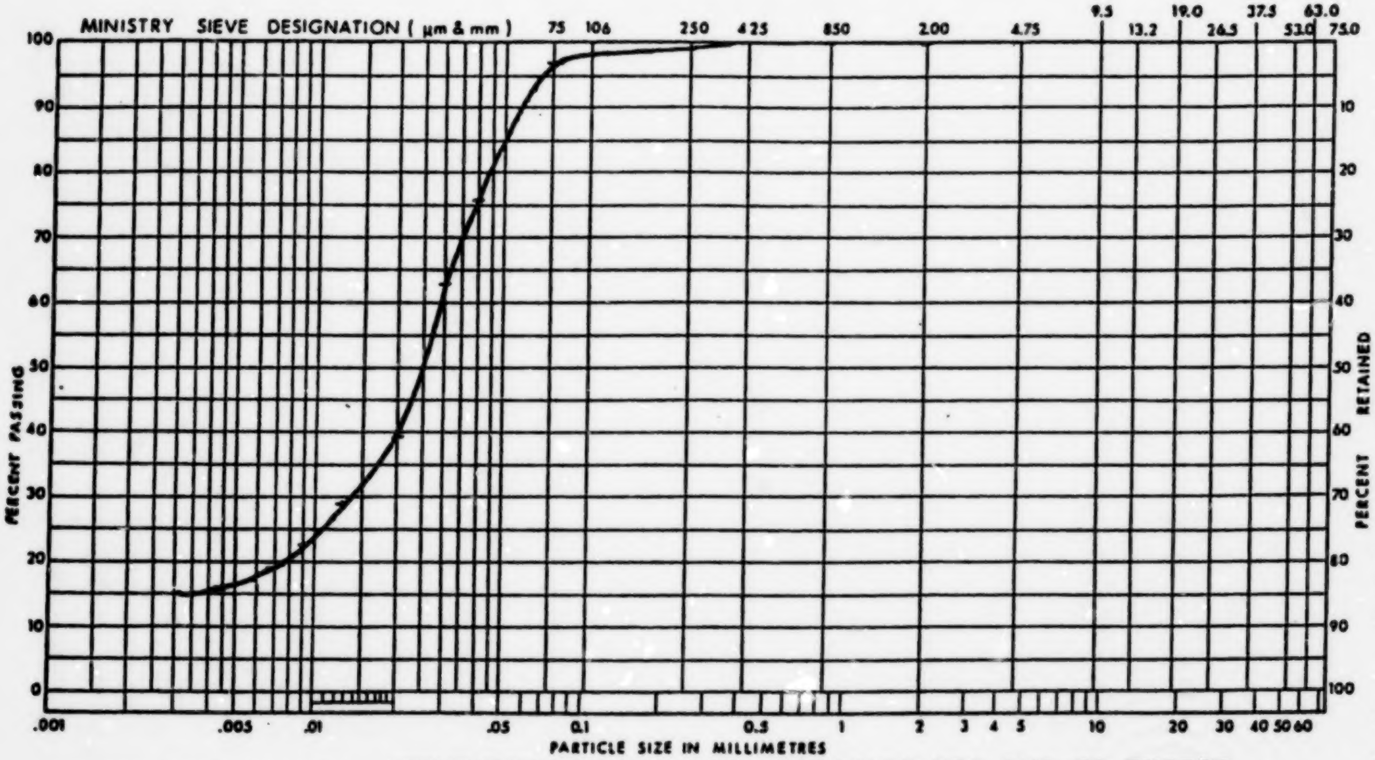
RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 11
% 5 - 106 µm 17
FROST SUSCEPTIBILITY

T.H. Nº 4 (0.2-4.0m)
85 A0 2020

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS OF FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100%
% PASSING 75µm 97%
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB SA. Si.

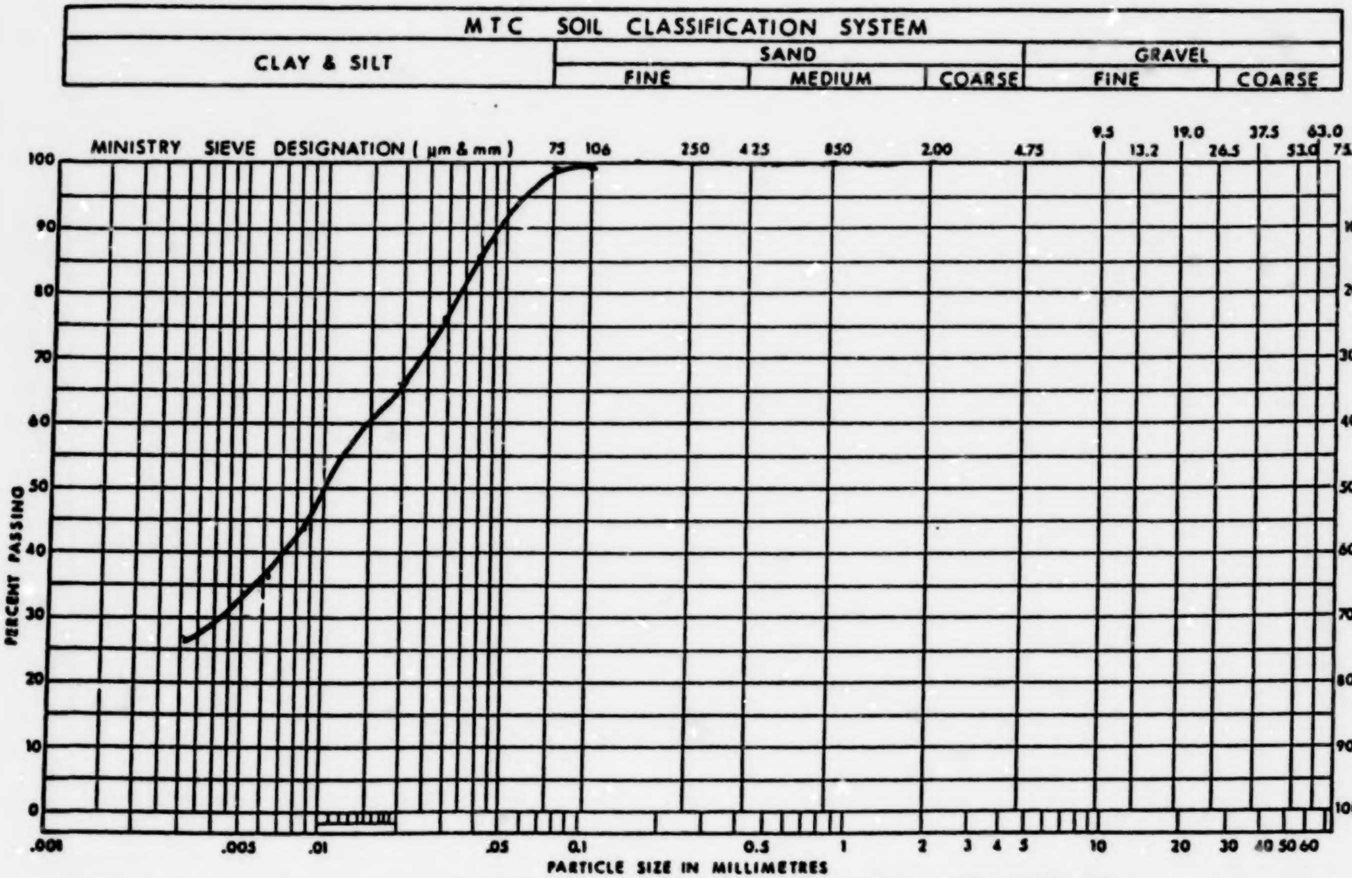
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 26.6 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 72%
% 5 - 106 µm 82%
FROST SUSCEPTIBILITY

T.H. Nº 4 (4.0-8.0m)
85A0 2021



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%
% PASSING 75 µm 99%
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB Cl. Si.

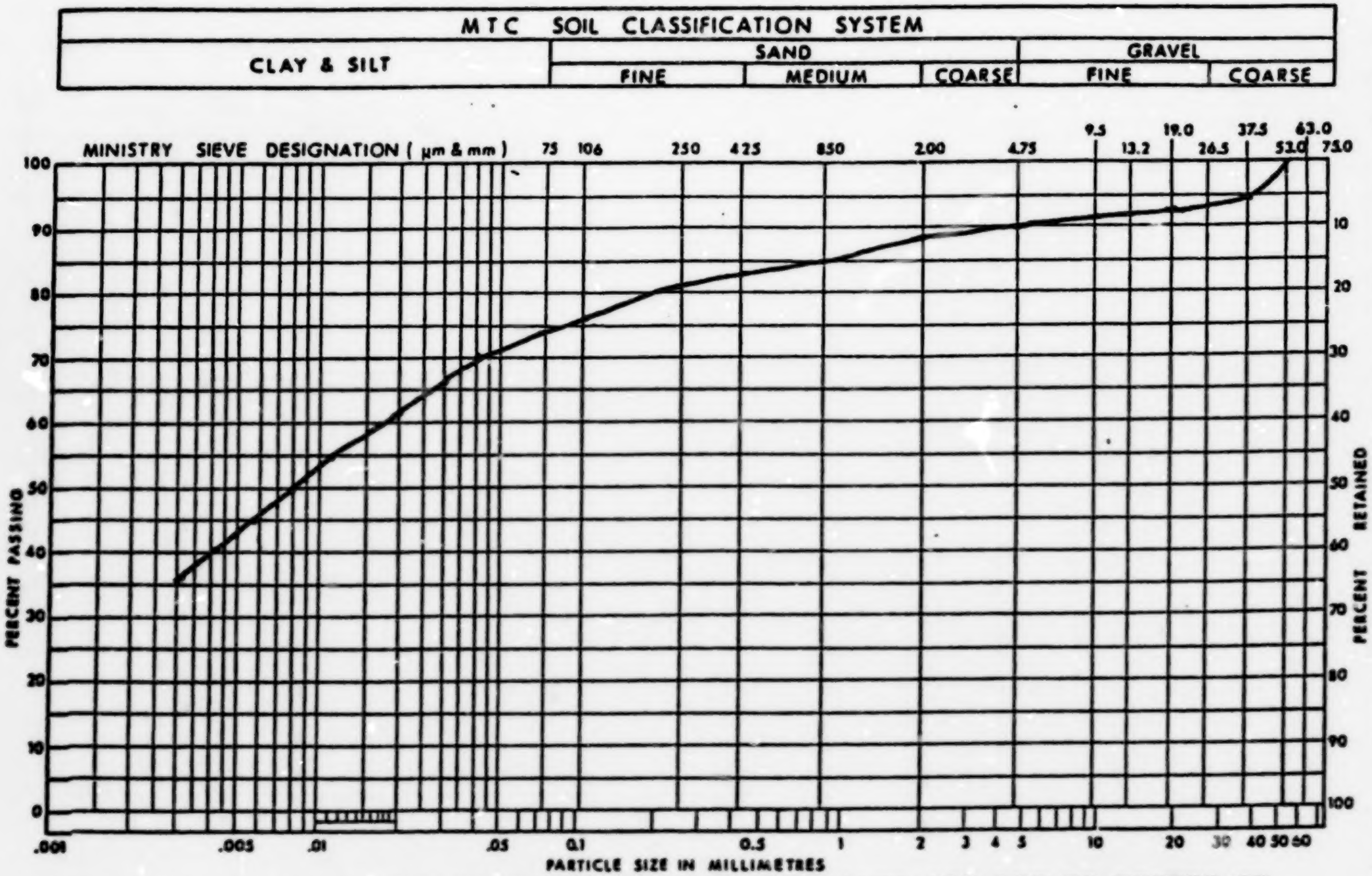
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 26.6 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 60%
% 5 - 106 µm 65%
FROST SUSCEPTIBILITY

T.H. Nº 4 (8.0-9.5m)
85A0 2022



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS OF FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm

% PASSING 75 µm 74%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB Si. Cl.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 19.6 %

% COMPACTION

FROST CRITERIA

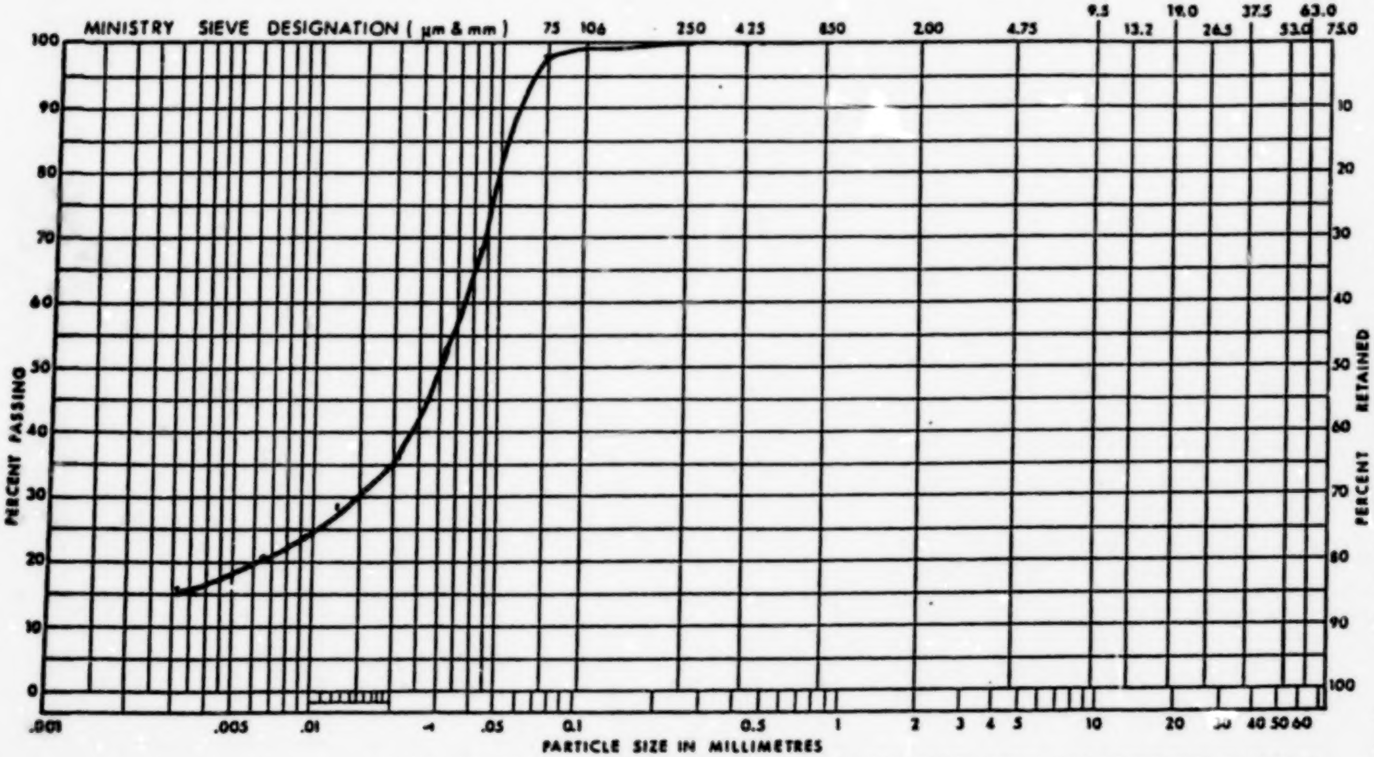
% 5 - 53 µm 32%

% 5 - 106 µm 37%

FROST SUSCEPTIBILITY

T.H. Nº 8 (5.0-8.0m)
85A0 2023

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100%

% PASSING 75µm 98%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \cdot D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB SA. Si.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 27.1 %

% COMPACTION

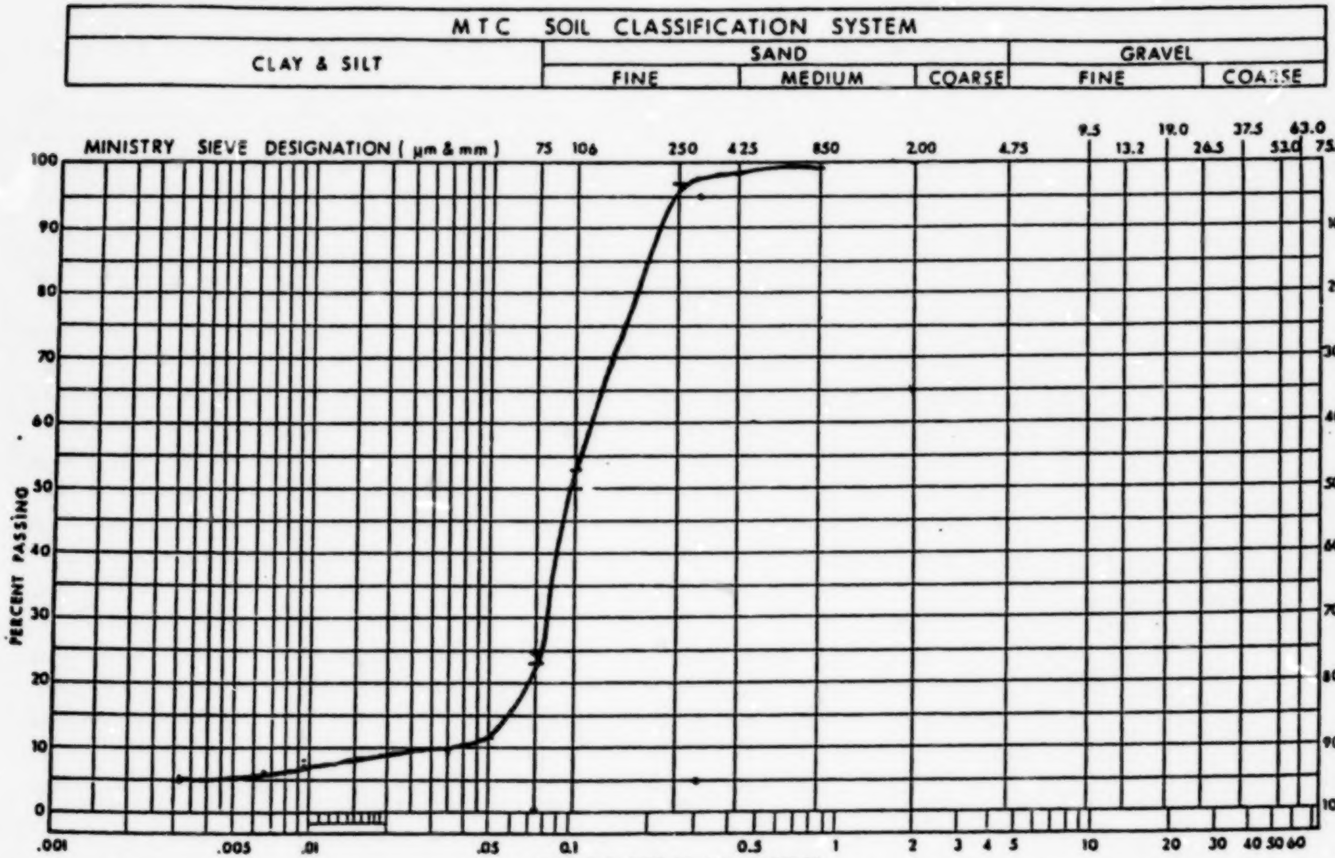
FROST CRITERIA

% 5 - 53 µm 69%

% 5 - 106 µm 81%

FROST SUSCEPTIBILITY

T.H. Nº 6 (0.2-5.0m)
85 A0 2024



REMARKS & RECOMMENDATIONS BORDERLINE FOR SELECT SUBGRADE MATERIAL DUE TO SLIGHT FINENESS OF GRADATION

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100%
% PASSING 75µm 23%
$C_u = \frac{D_{60}}{D_{10}}$ =
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ =
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX(I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB F. SA.

DENSITY

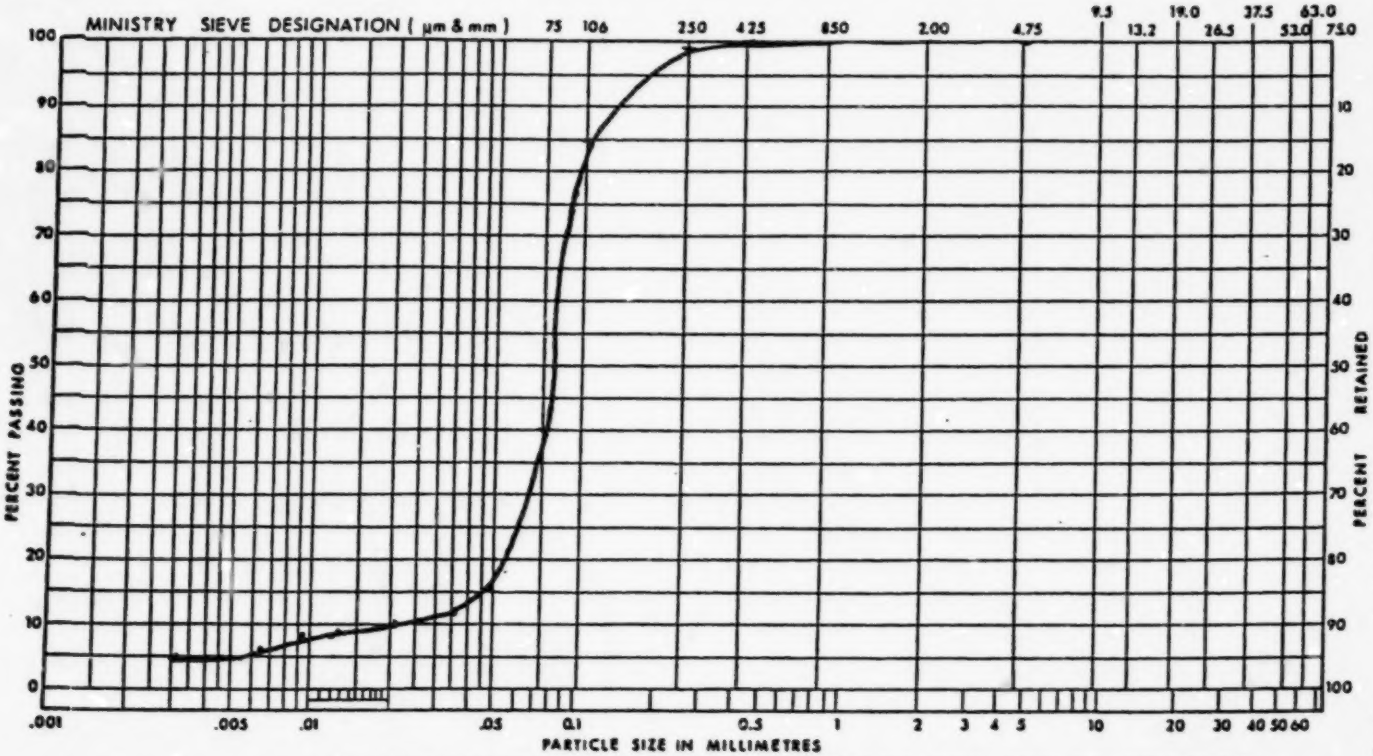
RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 13.3 %
% COMPACTION

FROST CRITERIA

SILT
% 5 - 53 µm 8%
% 5 - 106 µm 47%
FROST SUSCEPTIBILITY

T.H. Nº11 (0.2-5.0m)
85A0 2025

M T C SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO FINENESS OF GRADATION AND EXCESS FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100%
% PASSING 75µm 40%
$C_u = \frac{D_{60}}{D_{10}} =$
$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W$_L$) %
PLASTIC LIMIT (W$_P$) %
PLASTICITY INDEX (I$_P$) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB F. SA.

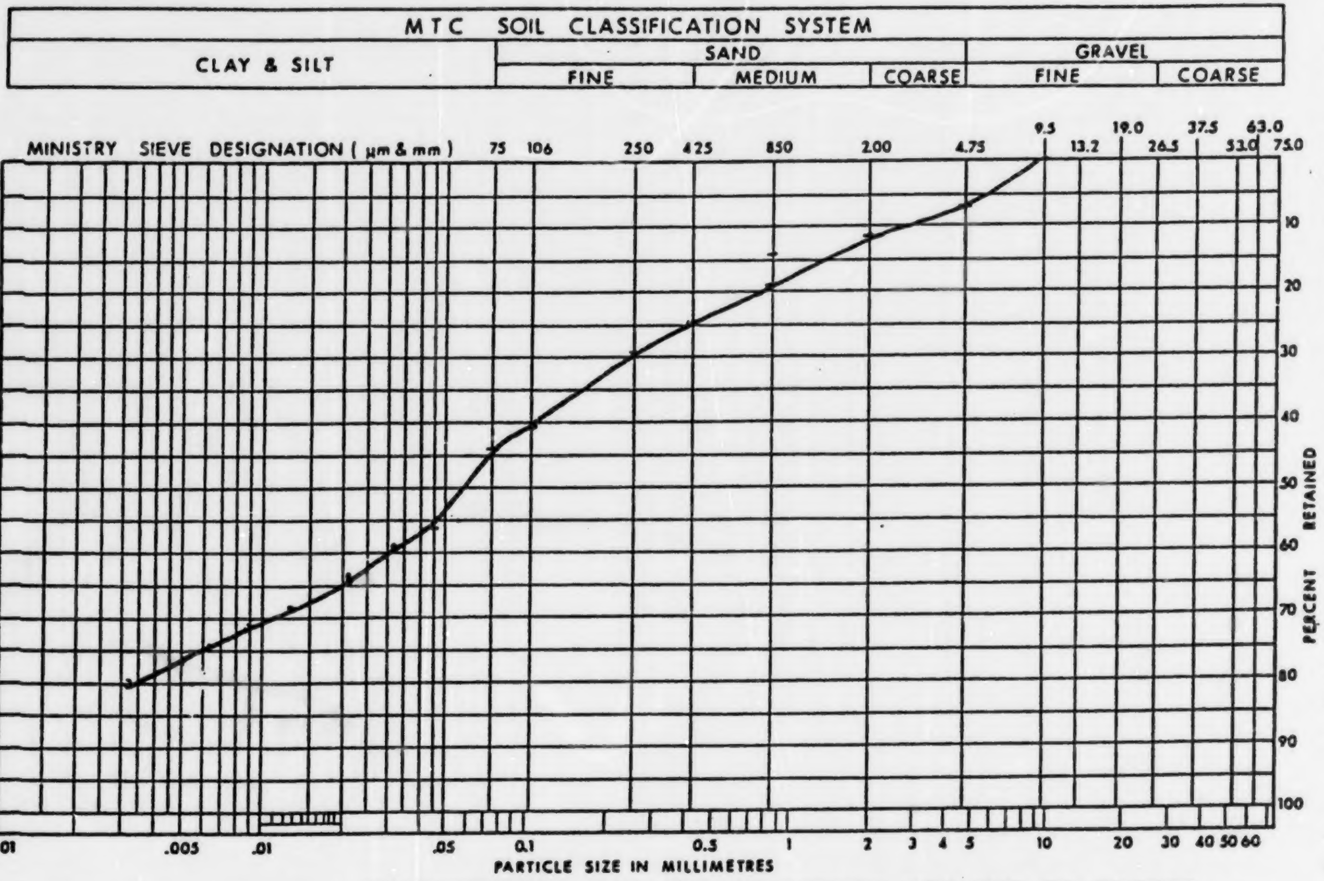
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT 25.0 %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm 13%
% 5 - 106 µm 80%
FROST SUSCEPTIBILITY

T.H. Nº 12 (11.0-12.5m)
85 A O 2026



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS OF FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 93%

% PASSING 75 µm 56.0%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB CL-SA.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 13.7 %

% COMPACTION

FROST CRITERIA

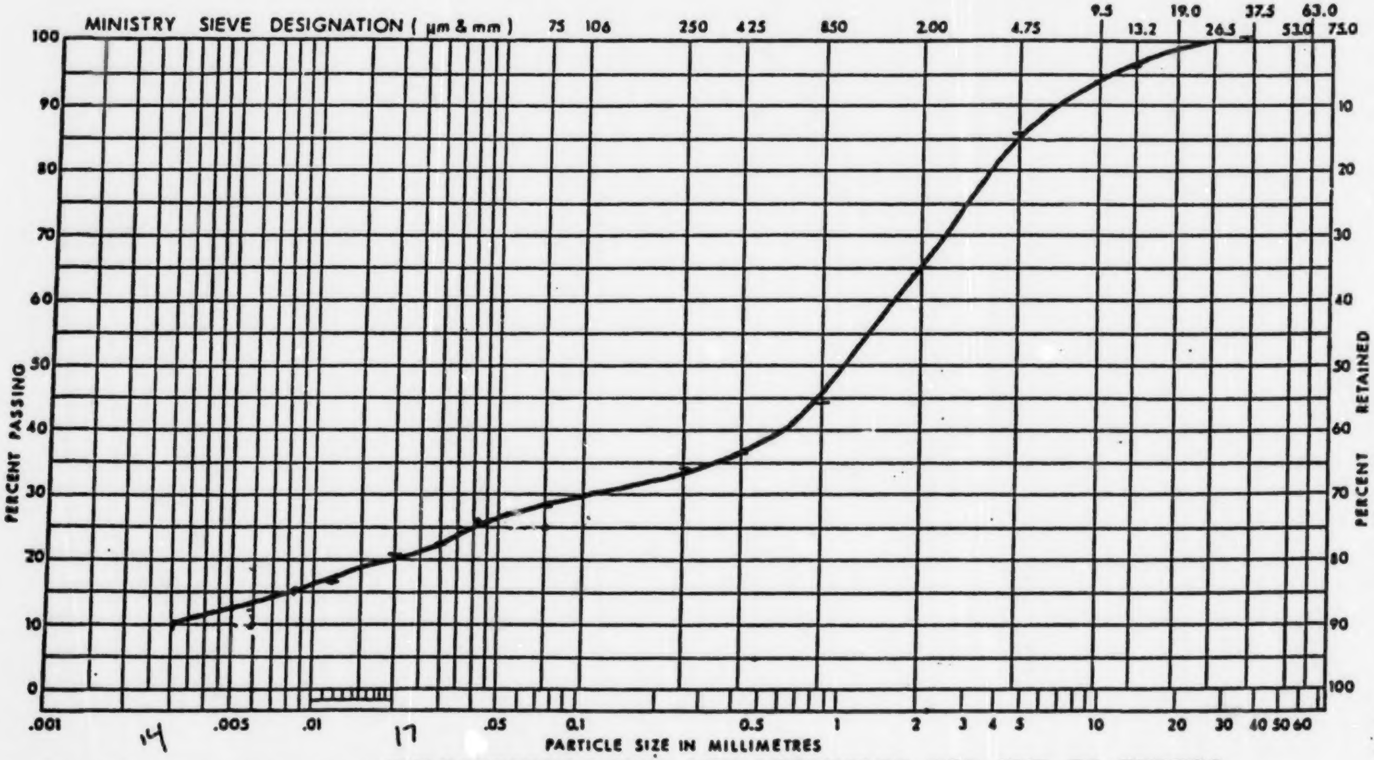
% 5 - 53 µm 26%

% 5 - 106 µm 38%

FROST SUSCEPTIBILITY

T.H. Nº 34 (0.2-5.0m)
85A0 2027

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS OF FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 86%

% PASSING 75 µm 28%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB SiSA.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 11.1 %

% COMPACTION

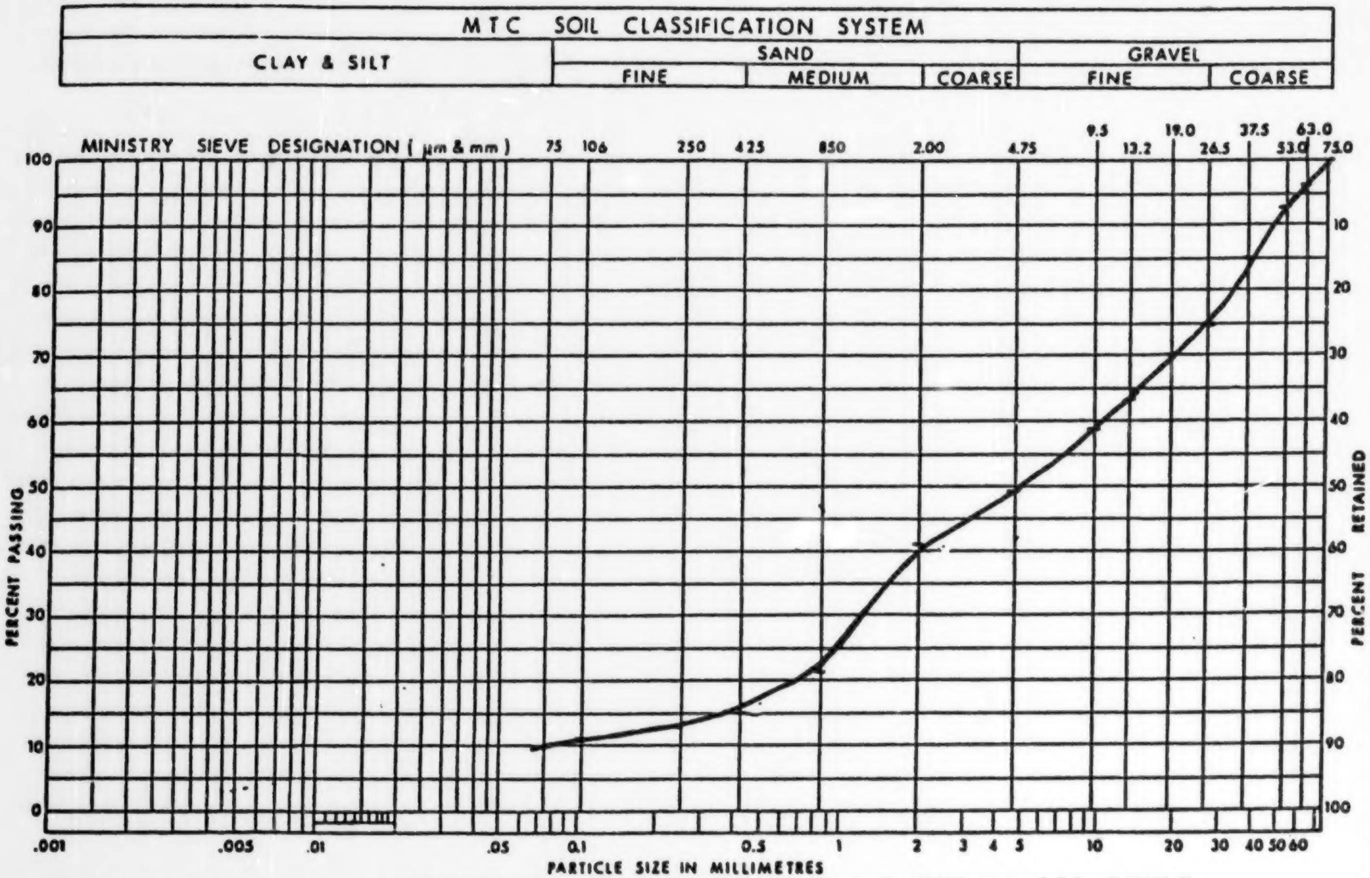
FROST CRITERIA

% 5 - 53 µm 17%

% 5 - 106 µm 21%

FROST SUSCEPTIBILITY

T.H. Nº 34 (6.0-9.0m)
85 A O 2028



REMARKS & RECOMMENDATIONS BORDERLINE FOR GRANULAR A & B DUE TO 10% FINES

DATE 86 04 10

SOIL PROPERTIES

% PASSING 4.75mm 49%
% PASSING 75µm 10%.
$C_U = \frac{D_{60}}{D_{10}} =$
$C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$
LIQUID LIMIT (W_L) %
PLASTIC LIMIT (W_P) %
PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD
LAB MED. SAND.

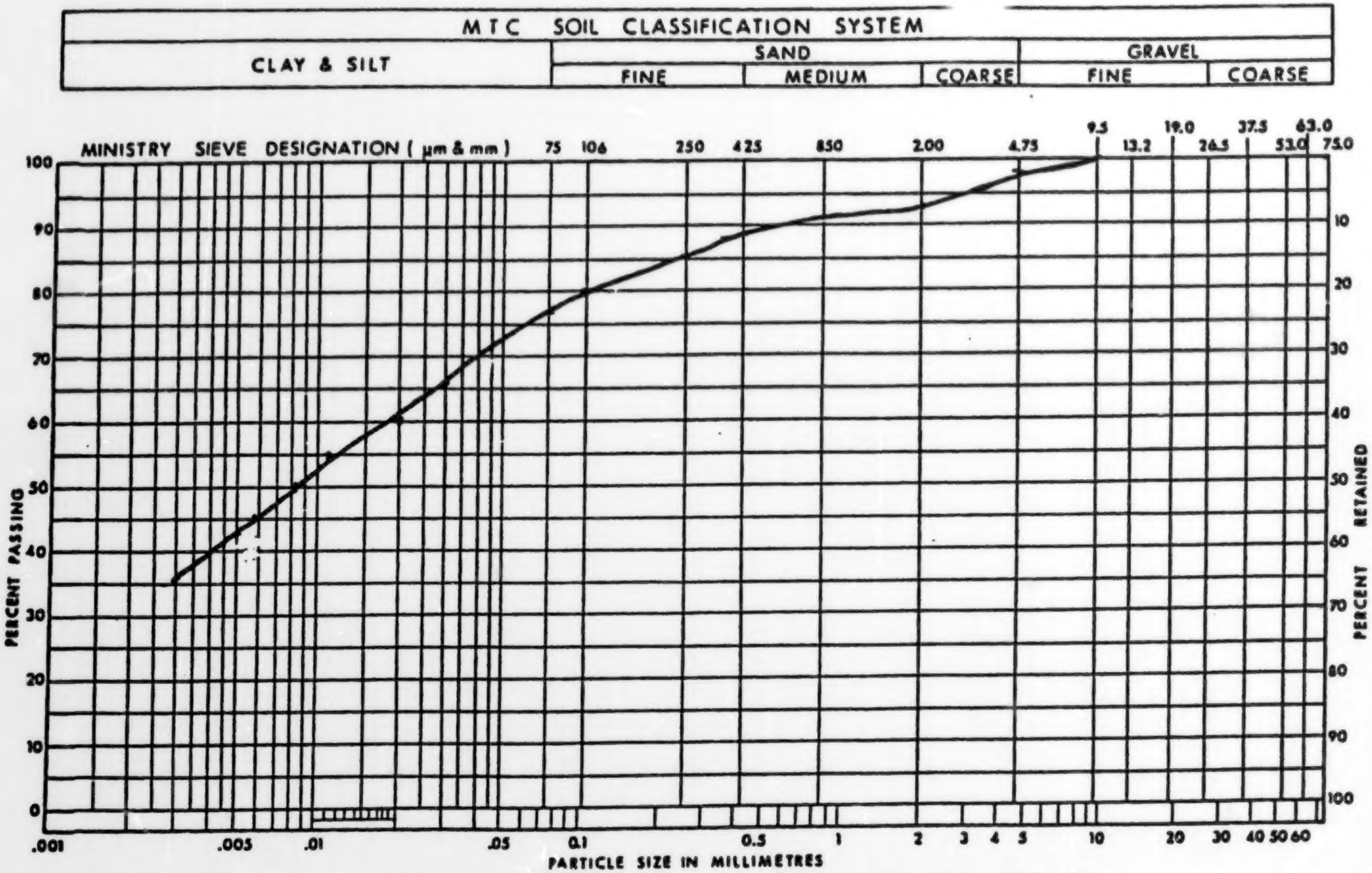
DENSITY

RELATIVE DENSITY
MAXIMUM WET t/m³
MAXIMUM DRY t/m³
OPTIMUM MOISTURE CONTENT %
FIELD WET t/m³
FIELD DRY t/m³
FIELD MOISTURE CONTENT %
% COMPACTION

FROST CRITERIA

% 5 - 53 µm
% 5 - 104 µm

T.H. Nº33 (0.2-7.0m)
85 A0 2029



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESS FINENESS

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 98%

% PASSING 75µm 77%

$C_U = \frac{D_{60}}{D_{10}} =$

$C_C = \frac{(D_{30})^2}{D_{10} \cdot D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB Si. Cl.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 18.0 %

% COMPACTION

FROST CRITERIA

% 5 - 53 µm 31%

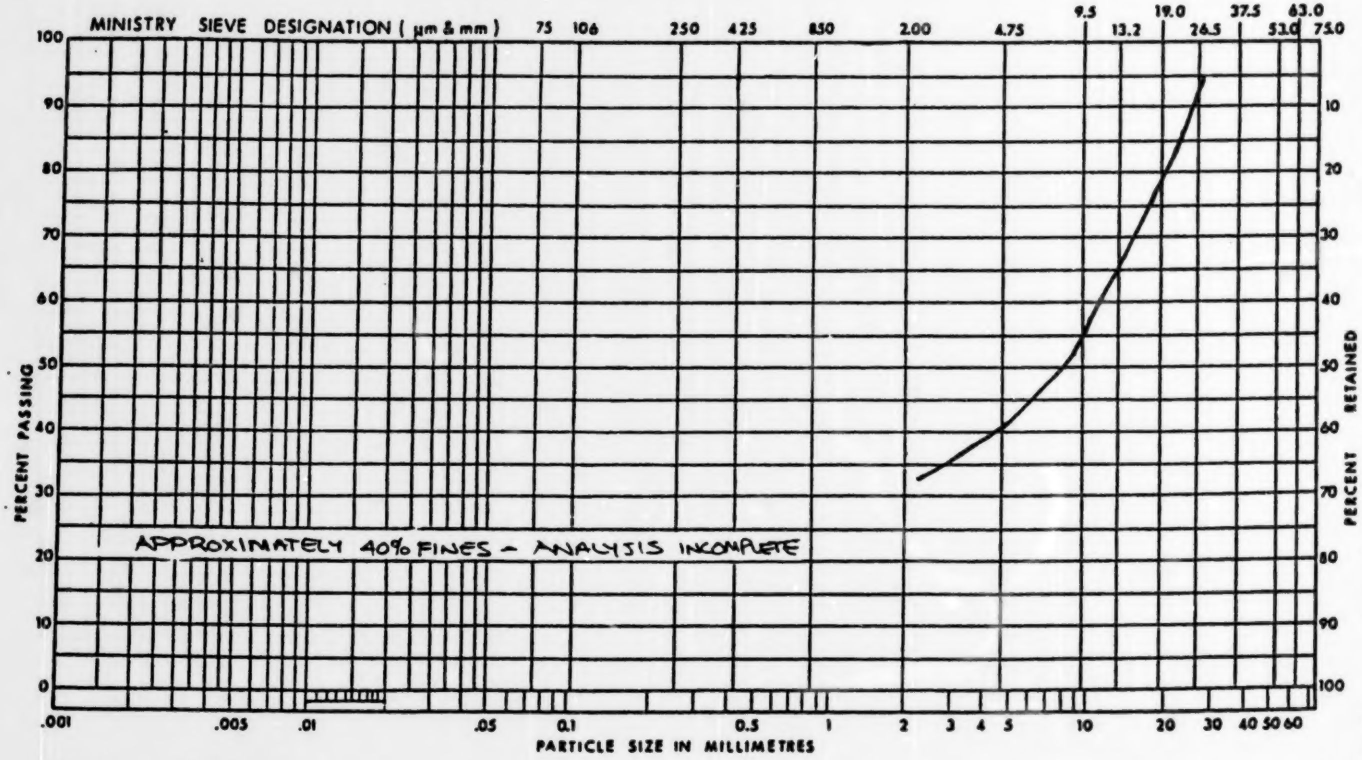
% 5 - 106 µm 38%

FROST SUSCEPTIBILITY

T.H. Nº 33 (7.0-8.0m)
85A0 2030

MTC SOIL CLASSIFICATION SYSTEM

CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



APPROXIMATELY 40% FINES - ANALYSIS INCOMPLETE

REMARKS & RECOMMENDATIONS ______

DATE ______ SIGNATURE ______

SOIL PROPERTIES

% PASSING 4.75 mm 40%

% PASSING 75 µm ______

$C_u = \frac{D_{60}}{D_{10}} =$ ______

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$ ______

LIQUID LIMIT (W_L) ______ %

PLASTIC LIMIT (W_P) ______ %

PLASTICITY INDEX (I_P) ______ %

CLASSIFICATION & GROUP SYMBOL

FIELD ______

LAB ______

DENSITY

RELATIVE DENSITY ______

MAXIMUM WET ______ t/m³

MAXIMUM DRY ______ t/m³

OPTIMUM MOISTURE CONTENT ______ %

FIELD WET ______ t/m³

FIELD DRY ______ t/m³

FIELD MOISTURE CONTENT ______ %

% COMPACTION ______

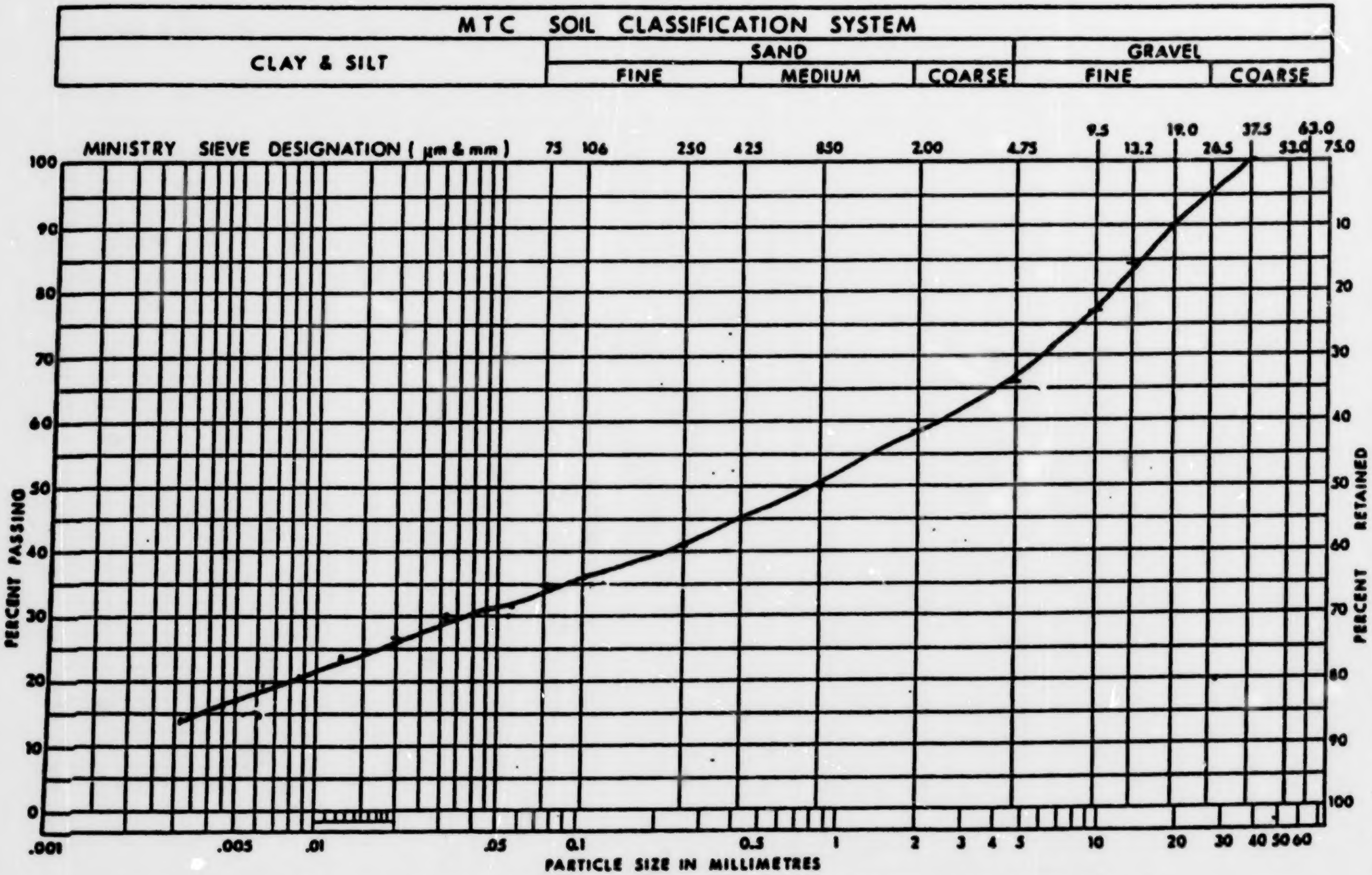
FROST CRITERIA

% 5 - 53 µm ______

% 5 - 106 µm ______

FROST SUSCEPTIBILITY ______

T.H. Nº 32 (4.0-4.5m)
85 A0 2031



REMARKS & RECOMMENDATIONS UNACCEPTABLE FOR ANY AGGREGATE USE DUE TO EXCESSIVE FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm

% PASSING 75µm 35%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB Si. SA.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT 4.0 %

% COMPACTION

FROST CRITERIA

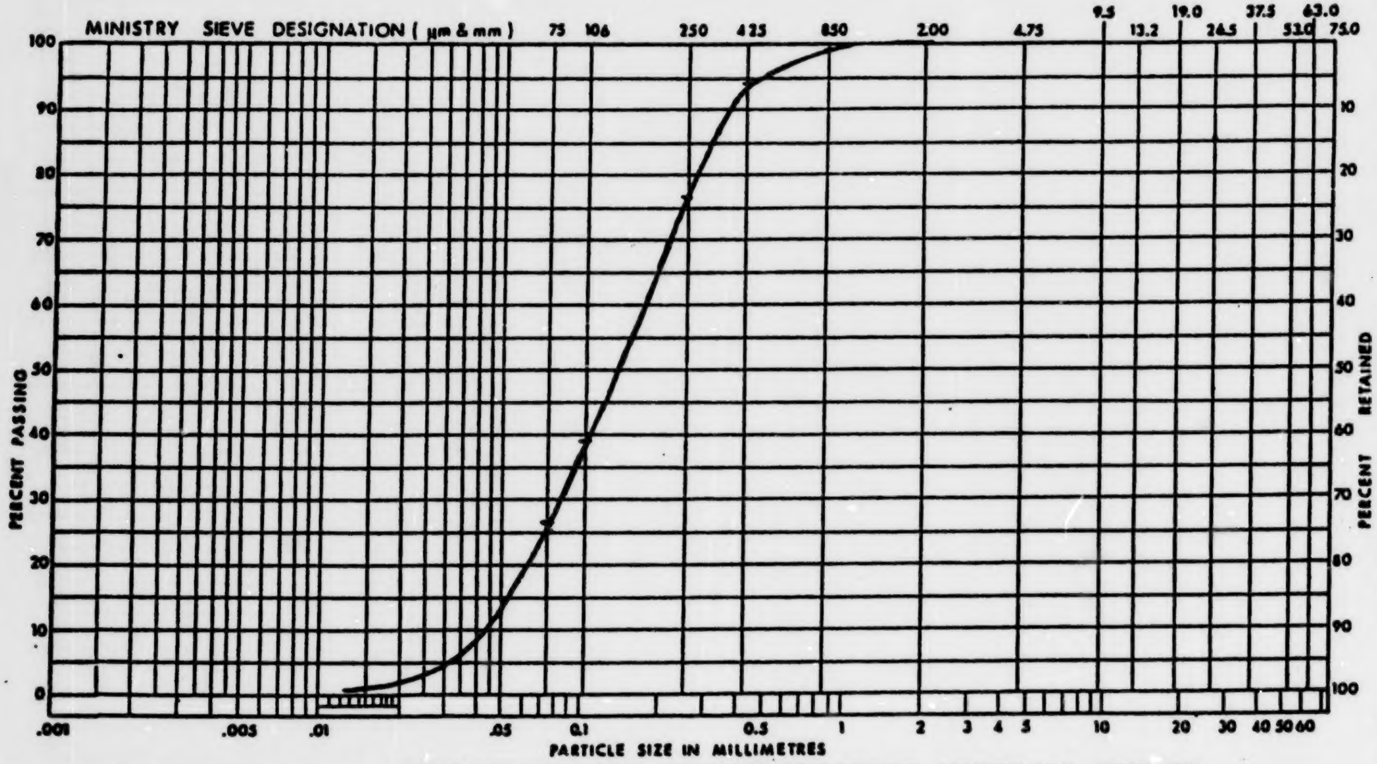
% 5 - 53 µm 30%

% 5 - 106 µm 36%

FROST SUSCEPTIBILITY

T.H. Nº 22 (4.0-11.0m)
85A0 2032

MTC SOIL CLASSIFICATION SYSTEM					
CLAY & SILT	SAND			GRAVEL	
	FINE	MEDIUM	COARSE	FINE	COARSE



REMARKS & RECOMMENDATIONS BORDERLINE FOR SELECT SUBGRADE MATERIAL DUE TO 27% FINES

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75 mm 100%

% PASSING 75µm 27%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB F. SAND.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT %

% COMPACTION

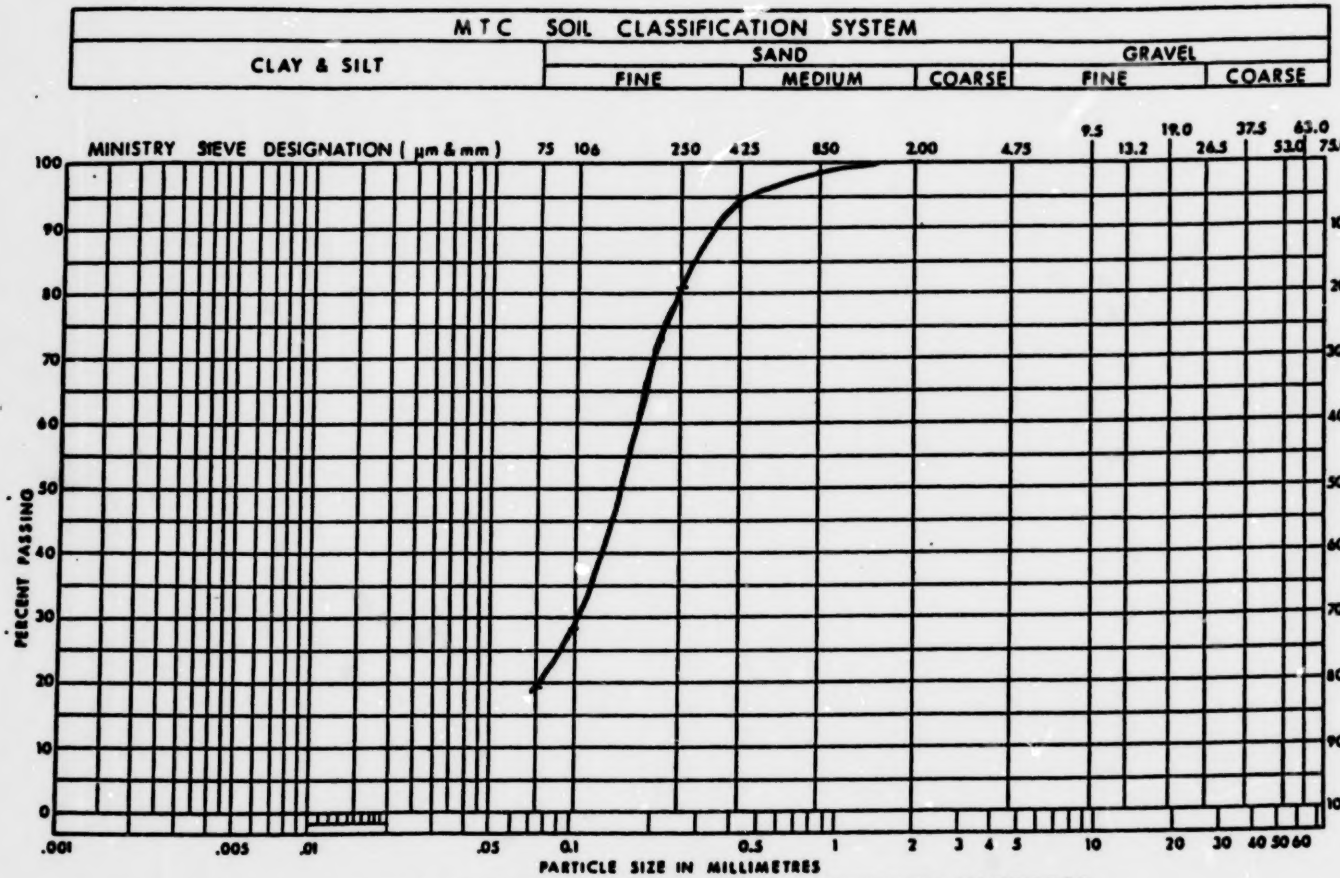
FROST CRITERIA

% 5 - 53 µm 13

% 5 - 106 µm 13

FROST SUSCEPTIBILITY

T.H. Nº 22 (11.0-12.5m)
85 A0 2033



REMARKS & RECOMMENDATIONS ACCEPTABLE FOR SELECT SUBGRADE MATERIAL

DATE 86 04 10

SIGNATURE

SOIL PROPERTIES

% PASSING 4.75mm 100%

% PASSING 75µm 19%

$C_u = \frac{D_{60}}{D_{10}} =$

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} =$

LIQUID LIMIT (W_L) %

PLASTIC LIMIT (W_P) %

PLASTICITY INDEX (I_P) %

CLASSIFICATION & GROUP SYMBOL

FIELD

LAB F. SA.

DENSITY

RELATIVE DENSITY

MAXIMUM WET t/m³

MAXIMUM DRY t/m³

OPTIMUM MOISTURE CONTENT %

FIELD WET t/m³

FIELD DRY t/m³

FIELD MOISTURE CONTENT %

% COMPACTION

FROST CRITERIA

% 5 - 53 µm

% 5 - 106 µm

FROST SUSCEPTIBILITY

APPENDIX D

MINISTRY OF NATURAL RESOURCES BOREHOLE DATA

Notes:

1. See Dwg. No.1 for borehole locations.
2. Strata depth and soil descriptions interpreted from Ministry of Natural Resources borehole logs.
3. Boreholes Nos. 1 to 5 logged by E.V. Sado, October, 1980.
4. Boreholes Nos. 6 to 13 logged by C. Welsh, June 16, 1981.

Borehole No.	Strata Depth (metres)	Soil Description
B.H. No.1	0 - 2.0	Si Sa Cl, W.T. @ 1.0 m
	2.0 - 4.0	F-VF Sa, some Si
	4.0 - 5.6	Si Sa Cl, some pebbles
	5.6 - 8.8	Si F Sa
	8.8 -11.9	Cl
	11.9 -15.8	Cl(y) Gr
B.H. No.2	0 - 3.5	Med-Co Sa
	3.5 - 5.2	F-Med-Co Sa - W.T. @ 4.9 m
	5.2 - 6.7	Med-Co Sa
	6.7 - 8.2	Co Sa - some pebbles
	8.2 -13.7	Co Sa
	13.7 -18.9	Gr(ly) Co Sa
	18.9+	N.F.P.
B.H. No.3	0 - 7.0	Si F Sa - W.T. @ 3.7 m
	7.0 -10.4	Si Cl
	10.4 -11.6	Co Sa
	11.6 -12.8	Cl(y) Si, some pebbles
B.H. No.4	0 - 0.9	Si F Sa
	0.9 - 3.3	Cl(y) Si
	3.3 -15.8	Co Gr
B.H. No.5	0 - 2.1	Med-F Sa
	2.1 - 5.2	Si Cl, some pebbles
	5.2 - 7.9	Co Gr
B.H. No.6	0 - 1.5	Dk Br Sa Cl
	1.5 - 2.4	Br Si Cl, some F Sa
	2.4 - 4.9	Gry Si Cl - wet
	4.9 -10.1	Cl, some pebbles - W.T.@ 6

Borehole No.	Strata Depth (metres)	Soil Description
B.H. No.7	0 - 1.5	Si F Sa
	1.5 - 2.4	Gry Br Cl(y) Sa
	2.4 - 7.0	Gry Si Sa, some Cl
B.H. No.8	0 - 1.2	Si F Sa
	1.2 - 2.1	Gry Br Cl(y) Sa
	2.1 - 6.7	Gry Si F Sa, some Cl - wet
	6.7 - 8.5	Gry Si Cl - wet
	8.5 - 9.7	Cl Till - wet
	9.7+	N.F.P.(Blds)
B.H. No.9	0 - 1.2	Med Sa
	1.2 - 3.0	Si Sa Cl
	3.0 - 4.0	Sa Cl
	4.0 - 6.4	Med Sa, some pebbles
	6.4 - 9.1	Med Sa
	9.1 -12.8	F Sa - wet
B.H. No.10	0 - 1.5	Si Sa
	1.5 - 3.4	Sa Si Cl
	3.4 -10.4	Med-Co Sa, some pebbles
	10.4 -13.1	Si F Sa
B.H. No.11	0 - 2.4	Sa Si Cl
	2.4 - 4.3	Cl(y) Sa, some pebbles
	4.3 - 7.3	Sa
	7.3 -10.7	Si Sa, some pebbles
	10.7+	N.F.P.(Blds)
B.H. No.12	0 - 3.0	Si Cl
	3.0 - 4.3	Cl Till
	4.3 - 5.2	Cl, some pebbles
	5.2+	N.F.P.(Blds)
B.H. No.13	0 - 1.0	Si Cl
	1.0 - 2.4	Cl Till
	2.4 - 3.0	Gr(y) Cl

APPENDIX E

ABBREVIATIONS FOR BORING AND TEST DATA

ABBREVIATIONS FOR BORING AND TEST DATA

Amor — Amorphous
Asph — Asphalt
BR — Bedrock
Blk — Black
Bl — Blue
Bld(y) — Boulder (y)
Blds — Boulders
BU — Break Up
Br — Brown
Cl — Clay
Co — Coarse
Cob — Cobbles
Comp — Compact
Conc — Concrete
Contam — Contaminated
Cord — Corduroy
Cr — Crushed
Dk — Dark
Decomp — Decomposed
E — Earth
Fib — Fibrous
w — Field Moisture Content
F — Fine
Fr Wat — Free Water
FB — Frost Boil
FH — Frost Heave
Gran — Granular
Gr — Gravel(ly)

Grn — Green
Grey — Grey
Hi — Highly
HM — Hot Mix
Lt — Light
Liq — Liquid
w_L — Liquid Limit
Matl — Material
Max — Maximum
MDD — Maximum Dry Density
MWD — Maximum Wet Density
Med — Medium
Mod — Moderate
Mott — Mottled
Mul — Mulch
NFP — No Further Progress
NFP (Blds) — No Further Progress (Boulders)
Num — Numerous
Occ — Occasional
w_{opt} — Optimum Moisture Content
Ora — Orange
Org — Organic
Org M — Organic Mattter
Ob — Overburden
Pavt — Pavement
Pedo — Pedological
Pen Mac — Penetration Macadam
w_P — Plastic Limit

I_P — Plasticity Index
PSty — Polystyrene
Poss — Possible
PST — Prime & Surface Treated
Quant — Quantity
Reinf — Reinforced
RF — Rock Fill
Sa — Sand
Sat — Saturated
Sh Rk — Shot Rock
Si — Silt(y)
Sl(y) — Slight(ly)
D_R — Relative Density
Stks — Streaks
Surf — Surface
Temp — Temperature
Tps — Topsoil
Tr — Trace
Unreinf — Unreinforced
Varv — Varved
VF — Very Fine
WT — Water Table
Weath — Weathered
Wd(y) — Wood(y)
Yel — Yellow

SUSCEPTIBILITY TO FROST HEAVING

HSFH — High
BSFH — Borderline
LSFH — Low

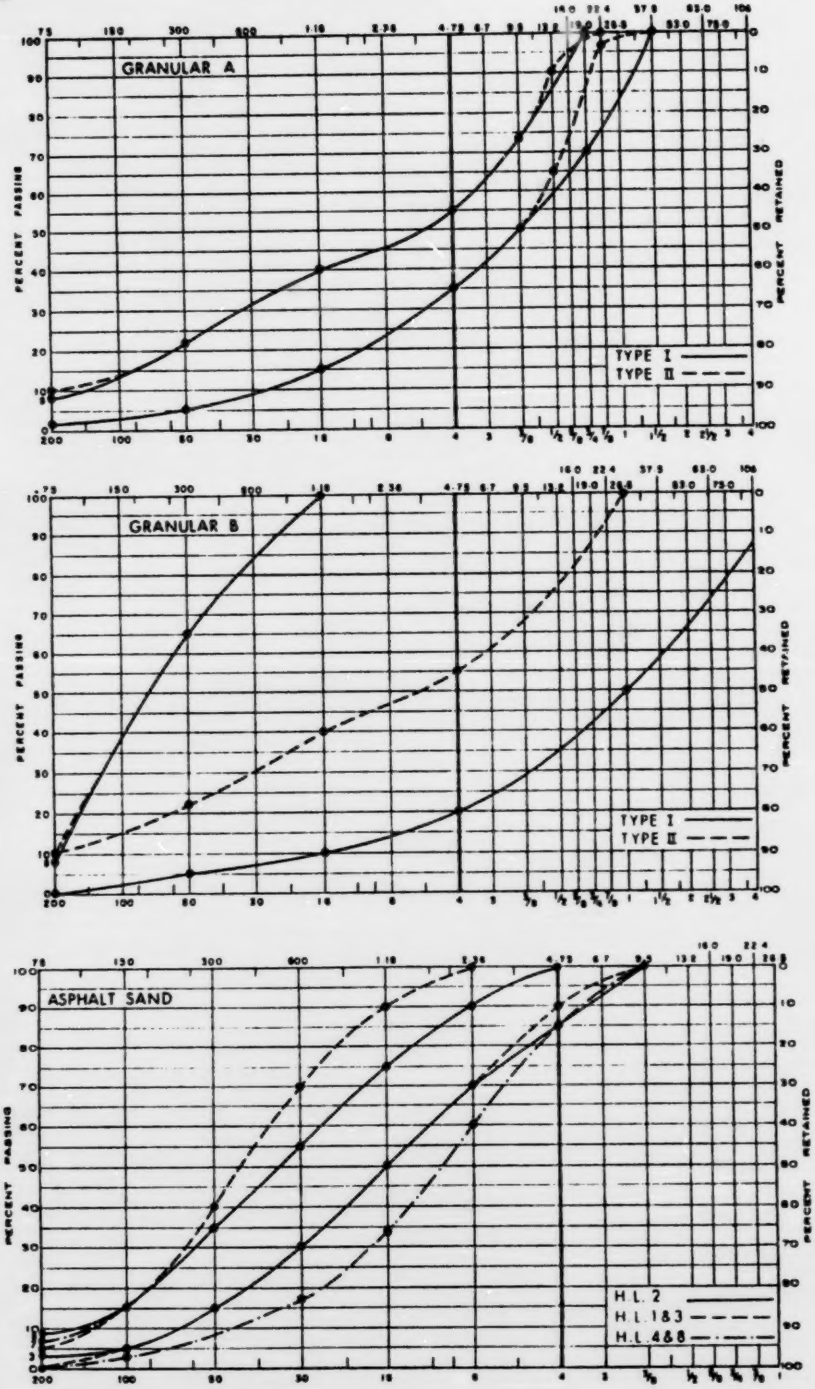
APPENDIX F

MTC AGGREGATE SPECIFICATIONS

Ministry of Transportation and Communications
Ontario

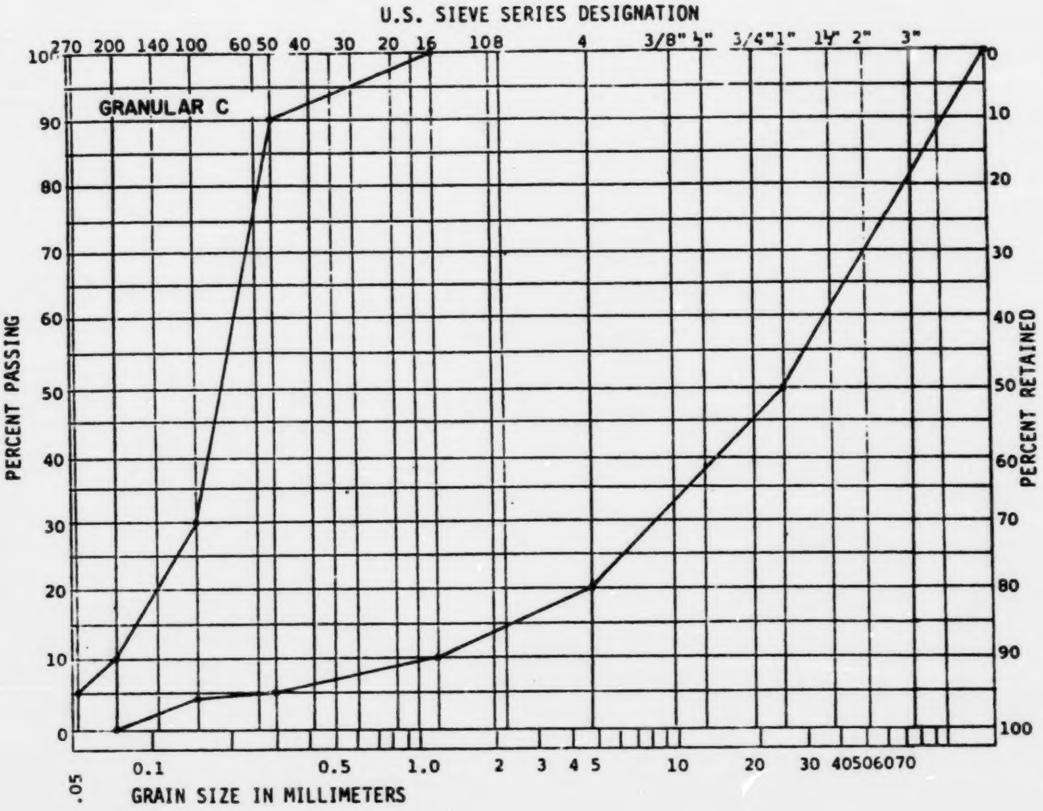
UNPROCESSED AGGREGATE GRADING CHART

MINISTRY SIEVE DESIGNATION



NOTE: SPECIFICATION POINTS INDICATED BY DOTS

PH-CC-310 83 09 (Formerly OB-MT-30)


U.S. SIEVE SERIES DESIGNATION
270 200 140 100 60 50 40 30 20 16 10 8 4 3/8" ½" 3/4" 1" 1½" 2" 3"
GRANULAR C
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
PERCENT RETAINED
0
10
20
30
40
50
60
70
80
90
100
.05
0.1
0.5
1.0
2
3
4
5
10
20
30
40
50
60
70
GRAIN SIZE IN MILLIMETERS